Development of Remote Machine System with Sense of Oneness

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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

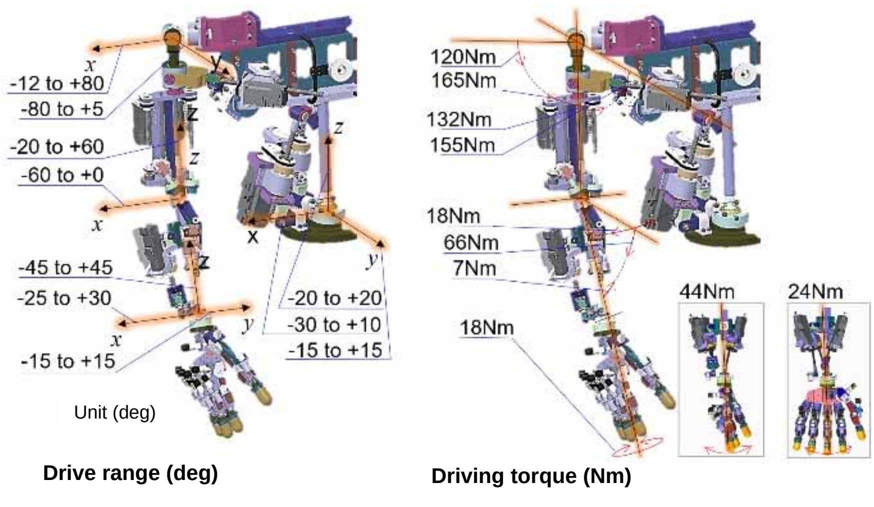

Fig. 1 Prototyped humanoid remote control robot

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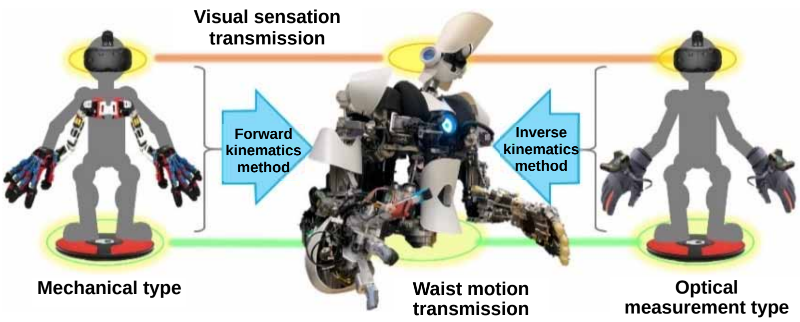
methods of achieving motion transmission: forward kinematics and inverse kinematics. We prototyped a mechanical type operation I/F that uses small arms as the forward kinematics method and an optical measurement type operation I/F that can measure 6 DOFs in the space at the fingers of an operator as 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.

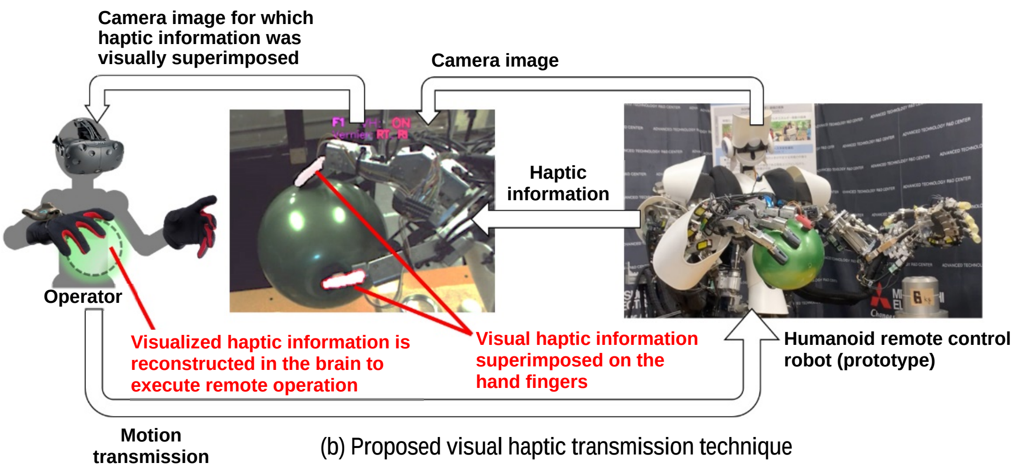
3.2 Simple visual haptic transmission technique that enables delicate operations

3.2.1 Existing haptic transmission technologies

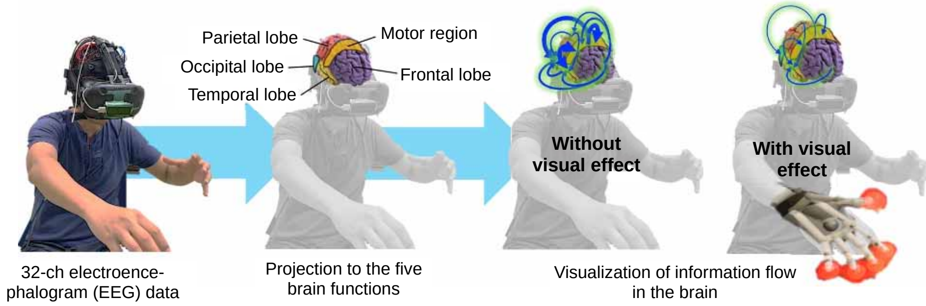
Methods of physically transmitting haptic information of remote machines include the installation and glove types. HaptX Gloves in particular are outstanding: the cutting-edge commercially available glove developed by HaptX Inc. has 30 points of force feedback (F/B) at each finger. However, the system



(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

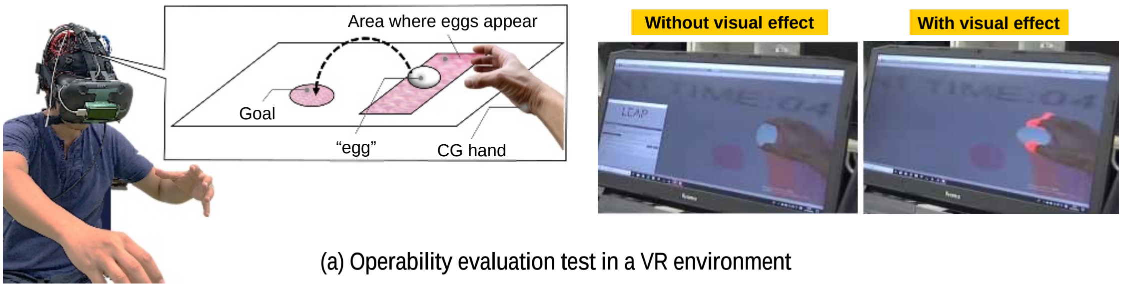
It is known that human haptic cognition is closely related with visual sensation. The da Vinci surgical system has shown that surgical operations are possible even without physical haptic information. Based on this knowledge and the authors' experience, in this project we aimed to simplify the operation 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

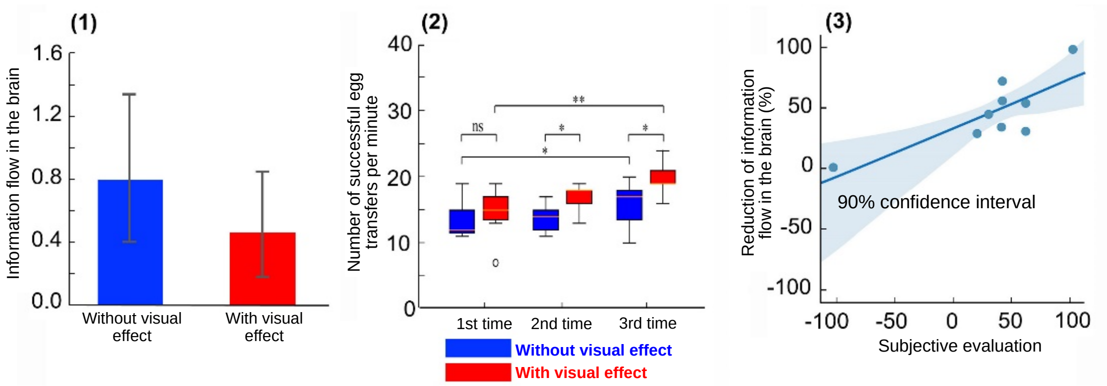
The operability of the proposed technique in which visual haptic information is superimposed on the contact points of the hands was analyzed and evaluated using electroencephalogram (EEG) measurement data and the smooth coherence transform (SCoT) library. SCoT is a technique for establishing a stationary 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]

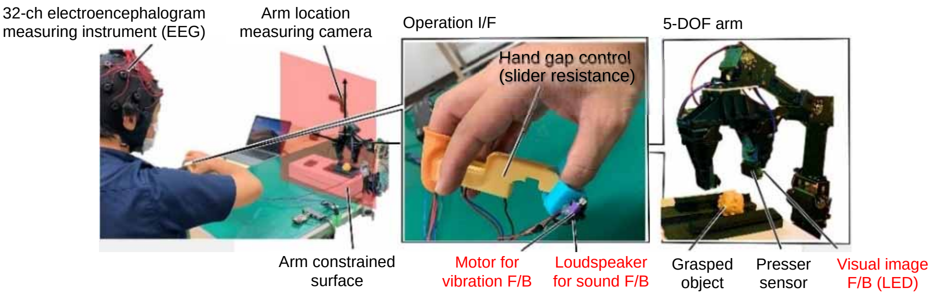
4. Verification of Operations with the Prototyped Humanoid Remote Control Robot System

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)).

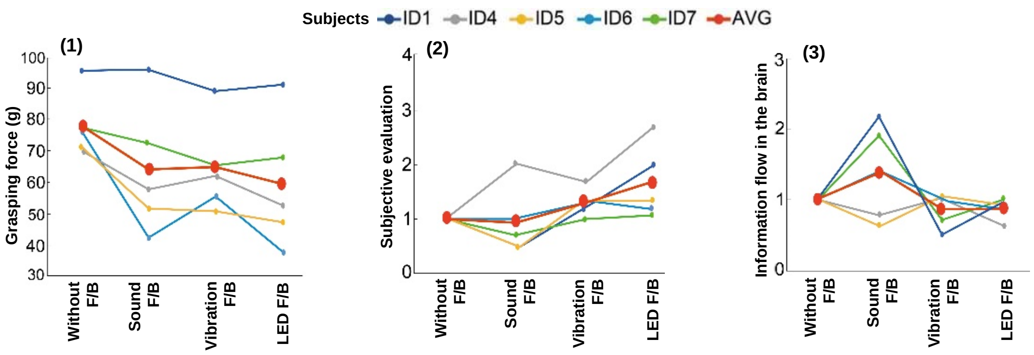
The proposed visual haptics technique was verified for three types of delicate operations: transferring a raw egg, potato chip, and card, and for grasping an alcohol container (Fig. 5(d)). The visual haptic information changes based on the grasping force. It has been confirmed that for all the objects, 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

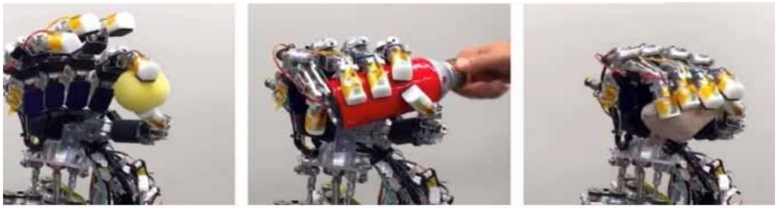


(a) Evaluation devices

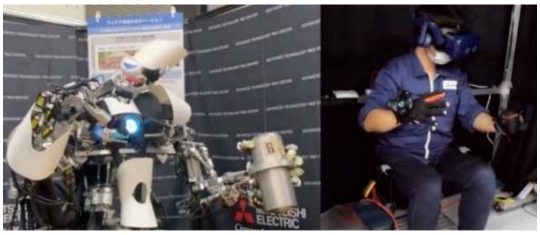


(b) Evaluation results

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



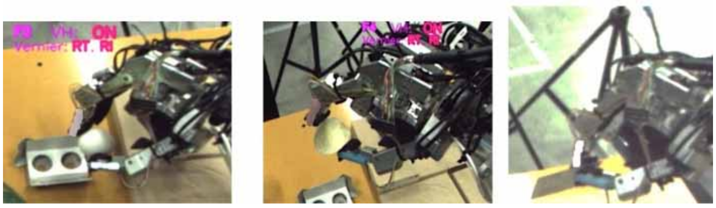
(a) Stable grasping by a hand with the self-locking mechanisms



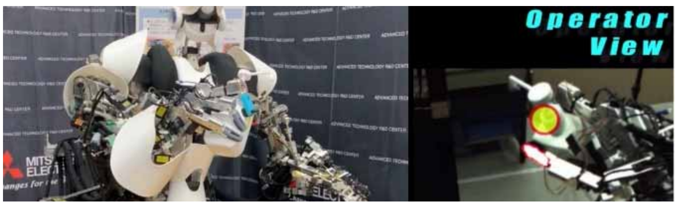
(b) High-power humanoid remote control robot that can grasp and transfer a 6-kg or heavier object with one arm

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

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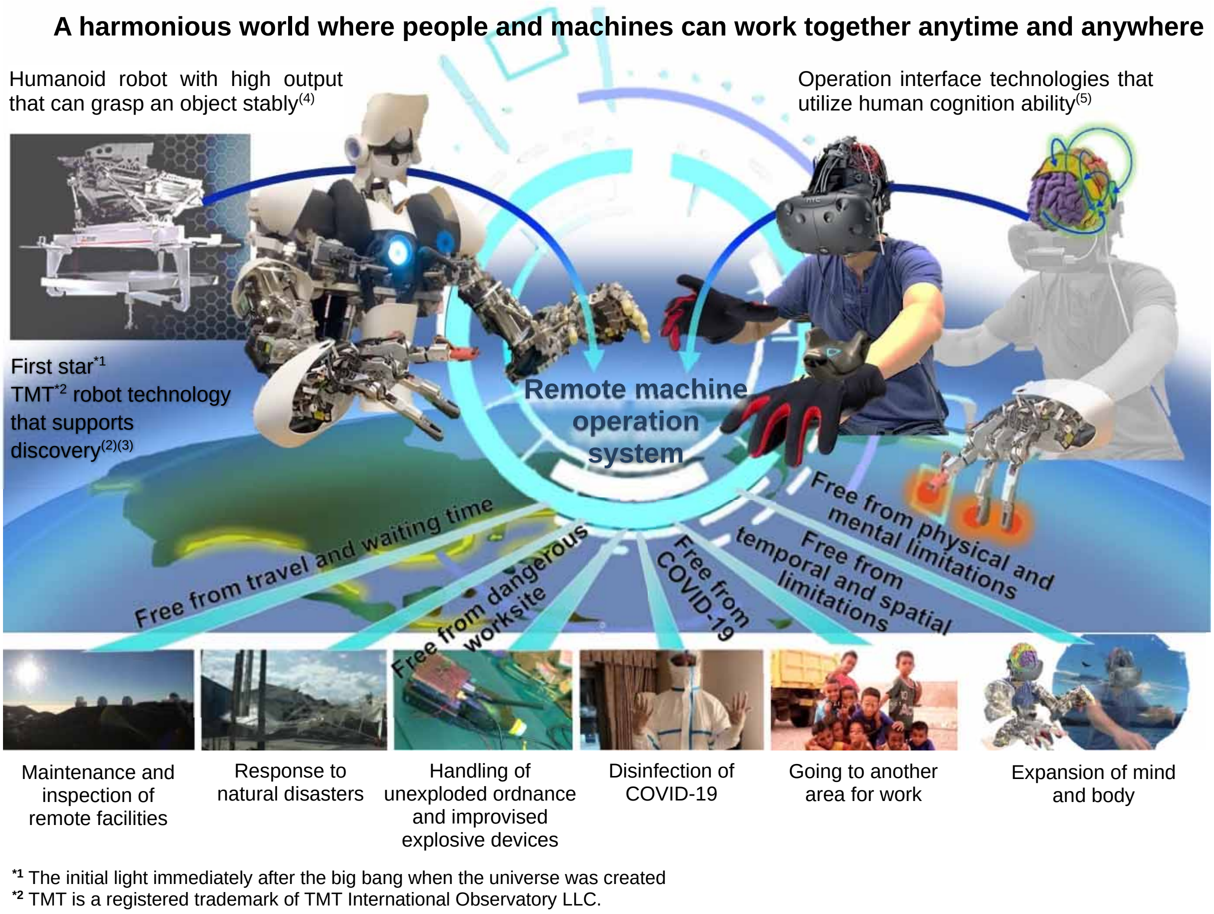

Fig. 6 A world where people and machines can live in harmony
"A harmonious world where people and machines can work together anytime and anywhere"

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

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