Haptic Communication Bilateral Control Teleoperation

Technology Reports

Special Articles on User Interface Research—New Interface Design of Mobile Phones—

Haptic Media for Innovative Real World Services

NTT DOCOMO is researching and developing haptic media as a third type of communication media following telephony (aural media) and video (visual media) with the aim of creating new services to meet diverse user needs. Haptic media can be divided into "touch media" for novel representation of interaction and "control media" for improving productivity in industry. The joint evolution of these two media will enable the creation of real world services in many fields to handle manual tasks and will lead to converged services with mobile communications.

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1. Introduction

As services evolve using a variety of media including voice, e-mail and video, the creation of attractive services that can satisfy increasingly diverse user needs is anticipated. In addition to services based on telephony (aural media) and video (visual media), NTT DOCOMO aims to cultivate new service fields through the use of haptic media as a third type of communication media. It is important that efforts be made to enrich human lives through communication media, which has the role of fostering human relationships. The sense of touch as a communication medium, however, is one area that has not been sufficiently cultivated. In fact, the development of technology for haptic media is still in progress. To achieve communication-oriented haptic media, the development of techniques that take the characteristics of networks into account is just as important as the development of devices and components. To this end, technical proposals for solving key issues are being made and characteristics of haptic media are being closely studied. Technical subjects that have a deep relationship with haptic media include touch displays and sensors, robotic device technologies, robust network techniques, advanced unmanned construction and bilateral control.

In this article, we divide haptic media into "touch media" and "control media" and describe our trials in developing related technologies for each.

2. Touch Media

NTT DOCOMO expects the joint evolution of touch media and control media together with device breakthroughs to enable the development of future ultra-realistic communications*1 (**Figure 1**).

Touch media pursues the possibility of new user interfaces and new ways of expressing tactile sensations. In this

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*1 **Ultra-realistic communication**: The concept of high-presence communications that can generate natural, shared sensations between remote locations by exploiting the five human senses including touch in addition to using audio and high-resolution video and multi-dimensional display.

type of media, sensations must be precisely measured and transmitted. When handling an object to find out more about it or doing something with an object in one's hands, the sense of touch plays a very important role. This sense of touch can be divided into cutaneous sensation and deep sensation. Cutaneous sensation is generated by receptors just under the surface of the skin and relates to how smooth or rough the surface of an object might be or whether an object is cold or warm to the touch. Deep sensation, in contrast, is generated by receptors located deep below the surface of the skin such as muscles and tendons and relates to how heavy or hard an object might be. Since expressions like "sense of touch" and "tactile sensation" are usually associated with cutaneous sensation, and considering that deep sensations are also important, we use the word "haptic" in this article to express both cutaneous and deep sensations.

2.1 Touch Displays and Sensors

Recent inventions in touch panels and sensors and in various types of devices have been truly remarkable, and research into touch displays and sensors has been quite active [1]. Mobile devices have become a big part of human lives, and the dramatic spread of mobile devices using the touch-panel system has shown that new devices can be extremely attractive to users depending on the way they are used. Furthermore, combining the touch panel with existing techniques and devices is still a promising option. One example is the addition of a vibration actuator to the touch panel, which has been shown to shorten the time required to perform certain tasks under noisy conditions [2].

There is also an electrocutaneous display (**Photo 1**) that aims to reproduce a tactile sensation through the electrical stimulation of nerves connected to receptors instead of using an external mechanical stimulus like vibrations [3]. This device has been used to successfully represent alphabetical characters, and because it requires no mechanical drive components, it is particularly compatible with mobile devices. Some issues, however, still remain, such as the variety of sensations that can be presented and the resolution and stability of the stimulus.

Touch displays and sensors can act as communication media. Real-time online gaming is an example of a communication service having low delay as a strong requirement. In 3GPP specifications, a one-way delay of less than 75 ms between terminals is preferred [4]. However, in the development and testing of a five-finger haptic display (**Photo 2**) for sensing the hardness of a virtual object through communications (conducted jointly with the Virtual Reality Laboratory (Iwata and Yano Laboratory) at the University of Tsukuba), it was found that the system could be affected by network delays even smaller than the above value for online gaming [5]. Here, the application of a

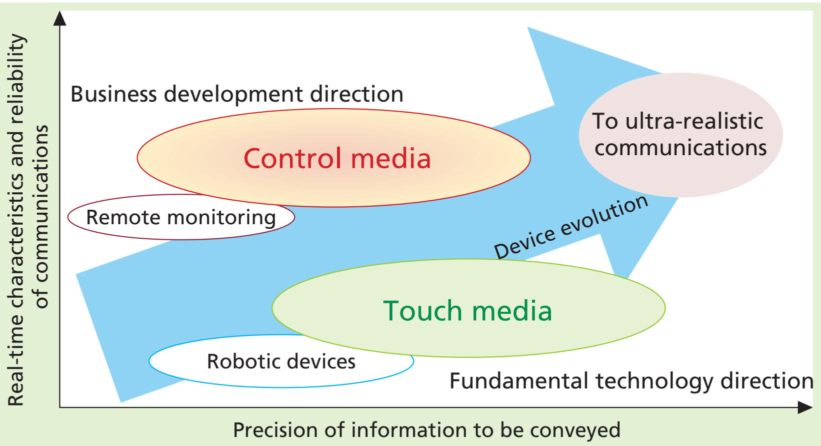

Figure 1 Direction of haptic and communication media

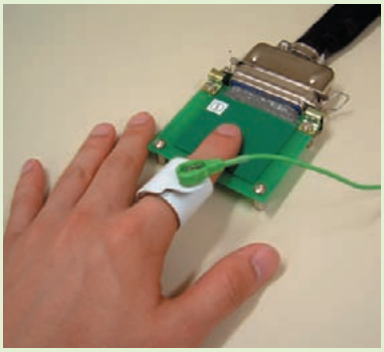

Photo 1 Electrocutaneous display

prediction method [6] can be effective in combating the effects of network delay in the case of a virtual environment, but a network with a delay as low as possible is preferable for conveying haptic sensations in the case of a real environment where contact prediction is difficult.

It is still difficult to achieve devices that can reproduce real haptic feedback in a mobile environment, but this is a field that requires step-by-step development of elemental technologies.

2.2 Robotic Device Technologies

We consider that actual robots could be used to achieve a medium that is intuitively easy to understand. At NTT DOCOMO, we have been researching new concepts in communication, one of which is an alter-ego interface that treats a robot as a type of wireless terminal providing a new communication medium (**Photo 3**). In the experiment shown in the photo, the subject uses a remote robot as his alter ego. The real-world actions that the subject performs through body movements or hand gestures are reproduced by the remotely located robot in real time via networks. The experiment thus aims to convey a sense of presence [7]. We have also been involved in a virtual-humanoid project. This project makes use of a robot having light, high speed arms developed jointly with the Space Machines Laboratory (Uchiyama and Konno Laboratory) at Tohoku University and a Head Mounted Display (HMD) for superimposing computer-generated graphics on that robot. The idea here is to achieve video that can be touched with the human hand. We proposed that the virtual humanoid could be used for conveying physical interaction and analyzed its potential for entertainment through the use of questionnaires [8]. Nonverbal communication can play an important role in certain situations, and in the future where robots will be more prevalent, we expect actual robots to be a useful user interface.

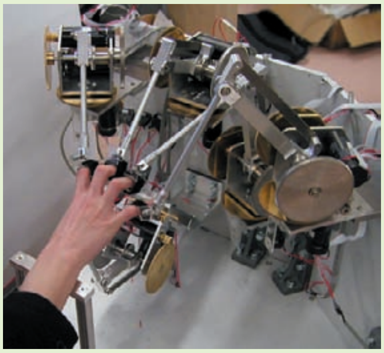

Photo 2 Five-finger haptic display

Photo 3 Alter-ego interface experiment

3. Control Media

Control media attempts to achieve both improvements in productivity and enhanced levels of safety while also creating new industries. In **Figure 2**, we see how the cost of communications has changed over time using various historic resources as reference. Traditional means of communication in the manner of couriers prior to the invention of telecommunications can be regarded as a real, expensive service in which a real-world object was carried from one place to another. In the modern world, however, all kinds of communication functions have become extremely efficient and a variety of inexpensive communication services have become available to anyone. While the construction and operation of a modern communication system can require much labor and time, individual communication sessions have become capable of exchanging huge amounts of information without direct human intervention, and virtual services, in which the time and location of work on the service-receiving side and service-providing side differ, have appeared. This ability to consolidate work over both time and space is a good example of technical innovation.

However, real world services that depend on manual labor still exist in a variety of fields such as agriculture, forestry and fisheries, construction and civil engineering, healthcare and nurs-

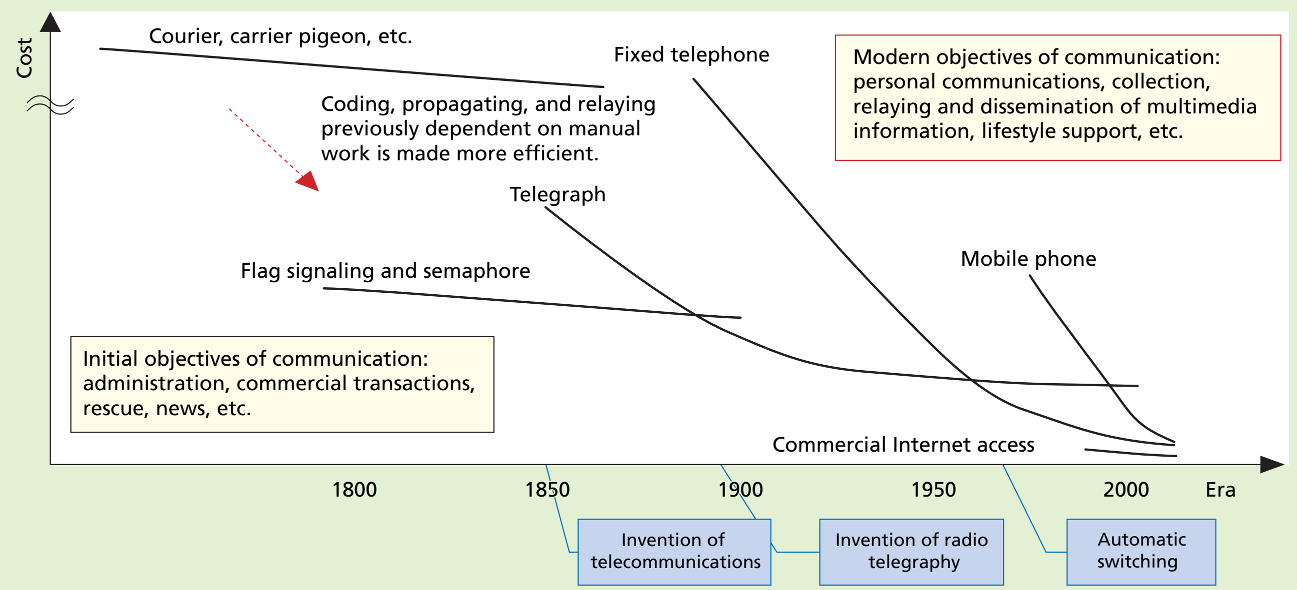

Figure 2 Historic changes in communications

ing, and education, and it is thought that not a few of these fields could become more productive through a merger with communications technology. To ensure reduced costs and reasonable quality services in such a merger, any improvements in productivity must be accompanied by safe and secure procedures. The work in each of these fields can therefore be divided into jobs that can be automated by machines as in remote monitoring and support and jobs that require cooperation between humans and machines as in teleoperation. In the latter type of jobs, high reliability and real-time operation that take the characteristics of communications into account is particularly important when advanced remote control needs to be performed while achieving safety and a centralizing effect through communications. We consider "control media" as introduced here to be one means of achieving reliability and real-time operation.

3.1 Technologies for More Robust Networks

Perception and action in humans depend on the functioning of the amazing human nervous system. The somatic nervous system, which relates to the outside world, includes efferent nerves that carry impulses from the central nervous system to the muscles and afferent nerves that carry impulses from the peripheral sensory organs back to the central nervous system. In teleoperation, the amount of afferent information is huge compared to the information used to convey commands for efferent movement. Afferent nerves correspond to the communication uplink on the far, teleoperated side, and the current mobile network, which in this sense acts predominantly as a downlink, is not necessarily optimized for teleoperation although it can cover a wide area of teleoperation work. It is therefore important that reliability be maintained by a technique that combines a variety of communication paths. We point out here that a slight delay in the transmission of information is usually not a problem in cases where people are referencing information with the exception of some applications like online gaming as mentioned above. However, in cooperative work between humans and machines or situations in which machines are using information, such a delay can be an issue, which makes it essential that switching time be shortened. With the aim of solving this issue, we have developed communication techniques [9][10] that can selectively use multiple communication paths. Here, however, a configuration corresponding to each application is required, and the need is felt for an implementation that is easier to use in conjunction with the further evolution of network and software technology.

3.2 Advanced Unmanned Construction

Unmanned construction is one application example of teleoperation using radio controls. There are already many examples of earthworks using remotely controlled machinery in a dangerous or access-restricted zone from a safe area outside that zone. The remote construction system, however, is dominated by commercial radio formats such as specified low-power radio[*2] or convenience radio[*3] in which radio resources[*4] are extremely limited. Communication distance and capacity are greatly limited as a consequence. With the aim of addressing this issue, we conducted unmanned construction experiments via the High Speed Downlink Packet Access (HSDPA) network in collaboration with Fujita Corporation and Caterpillar Japan Ltd. (**Figure 3**).

The effect of shortening the network delay and communication period on excavation efficiency was analyzed [11]. Given that communications during teleoperated construction is essentially in an always-on state, the number of pieces of machinery that are simultaneously connected and the communications environment of each site must be taken into consideration, but it was shown nevertheless that work efficiency could be improved by shortening the communication period compared to existing radio communication in unmanned construction systems.

In the above experimental setup, the FOMA terminals that exchange operation commands connect to servers in Japan's Kanto region, and it was demonstrated that teleoperation could be performed via a FOMA network despite a connection that included the transmission of long-distance IP packets having a round trip in excess of 1,000 km between the control side and an earthworks test site in Mt. Unzen Fugen-dake near Nagasaki, Japan. It was also shown that adding simple tactile feedback to the operation unit based on information received from the construction machinery could improve operability even for teleoperation of large-scale construction machinery by a

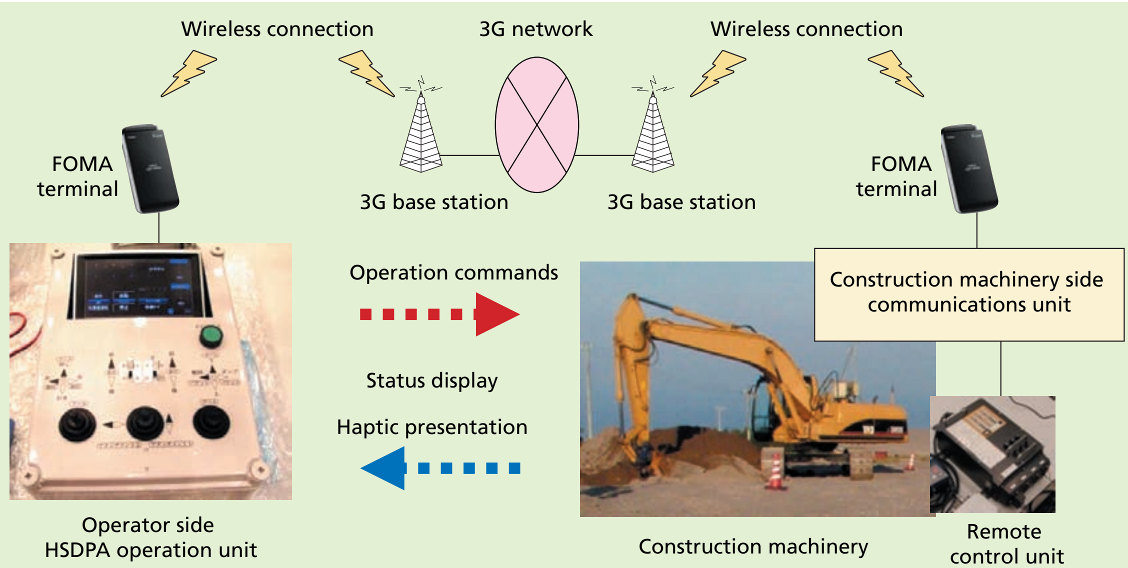

Figure 3 Experimental configuration for unmanned construction using a mobile phone network

*2 **Specified low-power radio**: A radio system that anyone can use without a radio station license. Transmitter power output is equal to or less than 0.01 W and the propagation distance is short at several hundred meters. In this system, 40 channels in the 429 MHz frequency band can be used for teleoperation, but since congestion can easily occur between nearby channels, frequencies must be appropriately selected when operating many pieces of machinery.

*3 **Convenience radio**: A radio system used for transmitting video, relaying radio signals, and other applications. It features broadband transmission in the 50 GHz band and a propagation distance of several kilometers, but suffers from strong directionality requiring continuous antenna tracking when mobile and disruptions caused by obstacles like construction machinery itself.

skilled field operator, In short, tactile feedback proved useful in addition to the usefulness of a GUI[*5] [12]. Unmanned construction is a field that can take advantage of the topographical characteristics of Japan and synergy with other fields; the accumulation of successful implementations and know-how is eagerly anticipated.

3.3 Bilateral Control

In teleoperation, safer, more efficient and more natural operations can be achieved by transmitting to the operator tactile sensations (haptic information) that indicate how the remotely located robot is interacting with its environment. This approach might also make possible delicate teleoperations that are not yet able to be performed. However, while obtaining and generating information do not directly affect each other in conventional audio and video communications, haptic communication is inherently bidirectional (bilateral) in which the law of action and reaction holds for the two remotely located parties. Because of these features, real-time information must be sent and received in a highly detailed manner especially when attempting to transmit subtle haptic information. This requirement, however, presents an issue in wireless networks. Even if the sessions can be held by making communications more robust as described earlier, retransmissions are bound to occur due to unavoidable channel fluctuations and error-recovery procedures. These retransmissions appear as "jitter" in network delay from the viewpoint of the application layer resulting in undesired haptic variations. Unpredicted disturbances, however, interfere with stable operations, and in response to this issue, NTT DOCOMO has researched and tested technology that can maintain stability in accordance with wireless network conditions in collaboration with Ohnishi Laboratory at Keio University [13]. Since position control and force control are basically incompatible (operability worsens when attempting to strictly synchronize position while position is difficult to determine when attempting to synchronize force), this technology achieves stability by performing control on the basis of acceleration—the common dimension between position and force—and by compensating for mechanical friction and communications-related disturbances. Furthermore, to enable the transmission of subtle haptic information, this technology incorporates lighter moving parts and high-speed controls. The experimental system that we have developed to evaluate this technology is shown in **Figure 4**. In this system, the master equipment on the operator side and the slave equipment on the remote side have the same configuration, and the control equipment on either side drives a direct-drive[*6] DC motor to manipulate an operation handle. The system measures handle activity using an optical rotary encoder[*7] and can detect a displacement of the handle tip on the order of 1 – 2 μm thereby providing precise position. The system also calculates and applies a wide range of force at intervals of 25 – 100 μs using the inertial moment of moving parts. Thus, by transmitting both position and force information in a bidirectional manner, it becomes possible to convey haptic information without the use of narrow-band or high-priced force sensors.

3.4 Exhibitions and Tests

In 2009, we presented two types of demonstration systems on haptic media. One of these was an Ethernet-based system for connecting master equipment with slave equipment and transmitting a variety of sensations, such as those of pushing a soft rubber ball or human hand, of touching and tracing a hard glass bottle by grasping a handle on the master side, and of feeling the smoothness and texture of certain objects. The purpose of presenting this system was to demonstrate the benefits of haptic media. The other demonstration system simulates a wireless network environment through the use of a network emulator. It was used to convey a sensation of vibration when remotely touching a guitar string, and in doing so, to promote an understanding of how haptic sensations can be conveyed by communication means. More than 1,000 visitors to this exhibition had an opportunity to experience these

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*4 **Radio resource**: In this article, frequency bandwidth, transmission power, etc. available to each user.

*5 **GUI**: A type of user interface that allows the user to submit instructions through intuitive operations based on a pointing device using computer-generated graphics on a display; a variety of devices have come into use to achieve accurate pointing.

*6 **Direct-drive**: A system that directly links the output of a motor's axis without the use of mechanisms like gears or belts. It features little play and precise control even for changes in rotation direction.

*7 **Optical rotary encoder**: A device that converts analog mechanical rotation to electrical pulses (digitally encoded stream) using optical devices and a rotating disk.

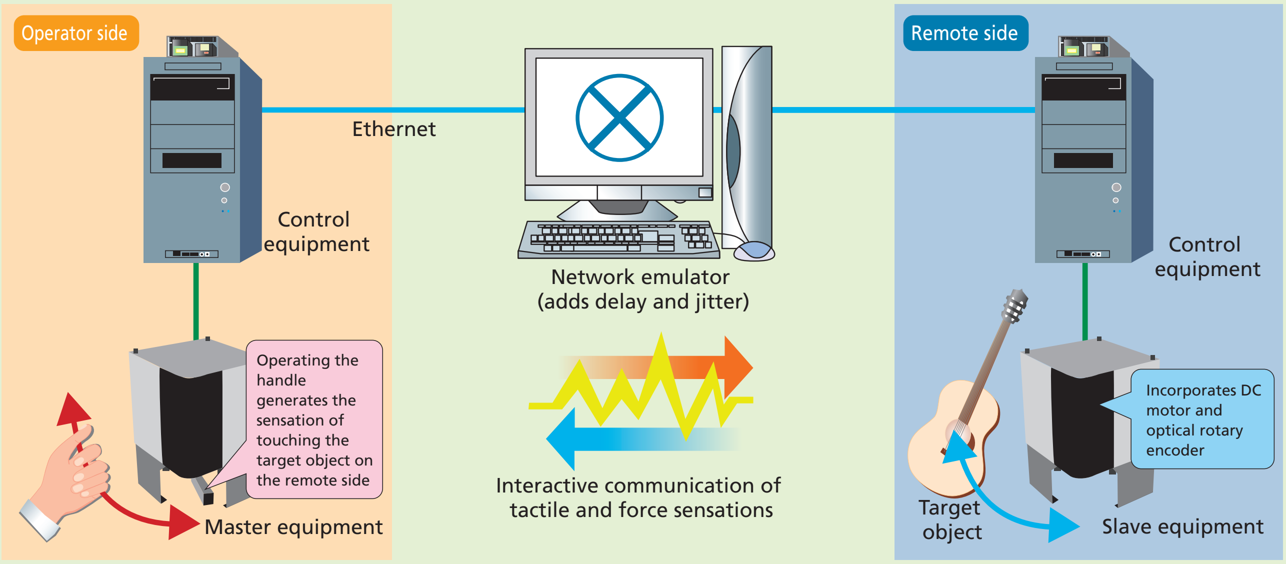

Figure 4 Experimental system for transmission of haptic information

systems, and by seeing for themselves how a variety of haptic sensations could be transmitted, they got a glimpse of future possibilities.

In addition to the above network emulator, we also evaluated the transmission of haptic sensations via an actual wireless LAN or HSDPA system, and we found that sensations became inferior as the delay and jitter increased under different conditions. The transmission of haptic sensations for target objects like cloth was hardly possible. We are still far from being able to transmit a wide range of haptic sensations that humans normally feel. Other issues surrounding the development of practical systems include downsizing, safety measures and multiple degrees of freedom, but we feel that further studies should help us accumulate useful knowledge on this new communication media.

4. Conclusion

In this article, we discussed the future possibilities of haptic media for communication purposes and described the communication characteristics and issues of various technical subjects associated with haptic media. Real-world perception and action performed as quickly and accurately as possible is essential to the survival of any life-form, and we consider that the transmission of sensations that people use as a matter of habit in their daily lives is a natural progression of communication technology into the future. To this end, we can expect that essential requirements for haptic communication will be met in LTE[*8] and beyond. However, as seen in the case of 3D video, which has been gathering much attention recently, haptic media is a field in which it is more difficult to predict how it will spread in the market than to create its direction. For this reason, we seek to create new value with haptic media by adopting a broad perspective and collaborating with experts in various domains.

REFERENCES

[1] S. Hiroyuki et al.: "Special Issue: Measurement and Control," Journal of the Society of Instrument and Control Engineers, Vol. 47, No. 7, pp. 547-615, Jul. 2008 (in Japanese).

[2] M. Fukumoto and T. Sugimura: "Active click: tactile feedback for touch panels," In Conference on Human Factors in Computing Systems, ACM, pp. 121-122, 2001.

[3] K. Hayashi et al.: "Objective Evaluation of Tactile Sensation for Tactile Communication, NTT DoCoMo Technical Journal, Vol. 7, No. 3, pp. 39-43, Dec. 2005.

*8 **LTE**: Extended standard for the 3G mobile communication system studied by 3GPP.

[4] 3GPP TS22.105 V9.0.0: “Services and service capabilities,” 2008.
[5] T. Tamura et al.: “Evaluation of Five-finger Haptic Communication with Network Delay,” NTT DoCoMo Technical Journal, Vol. 9, No. 3, pp. 52-56, Dec. 2007.
[6] Y. Kawano, M. Miyata, D. Hanawa and T. Yonekura: “The System Design and Evaluation of Real-Time Web Games with Dead Reckoning,” D - Abstracts of IEICE Transactions on Information and Systems, Vol. J91-D, No.12, pp. 2833-2843, Dec. 2009 (in Japanese).
[7] H. Nakano et al.: “Special Articles on Communications based on New Human-Interfaces—Towards the Creation of New Communication Services—,” NTT DoCoMo Technical Journal, Vol. 5, No. 1, pp. 4-69, Jun. 2003.
[8] K. Miura, A. Konno and M. Shoji: “Virtual Humanoid Physically Interactive with Humans,” Transactions of the Virtual Reality Society of Japan, Vol. 12, No. 3, pp. 305-314, Sep. 2007 (in Japanese).
[9] K. Hayashi, T. Tamura, M. Takahata and E. Minoru: “Mobile Communication Module for Teleoperated Robot,” Journal of Robotics Society of Japan, Vol. 26, No. 3, pp. 277-283, Nov. 2008 (in Japanese).
[10] T. Tamura et al.: “Seamless Traffic Migration between the Mobile and Fixed Networks,” NTT DOCOMO Technical Journal, Vol. 11, No. 1, pp. 33-40, Jun. 2009.
[11] K. Hayashi, T. Tamura and H. Miki: “Effects of Nework Delay and Period on Work Efficiency in Unmanned Construction and Method for Improving Efficiency,” Symposium on Construction Machinery and Methods, No. 23, Nov. 2009 (in Japanese).
[12] K. Hayashi, T. Tamura and M. Takahata: “Improving Teleoperation Performance using an Excavator with Tactile Feedback,” The Robotics Society of Japan, 3H3-05, Sep. 2009 (in Japanese).
[13] M. Takahata et al.: “Haptic Communication Technology Using Real-time Robotics,” NTT DoCoMo Technical Journal, Vol. 9, No. 3, pp. 57-61, Dec. 2007.