Telexistence: Enabling Humans to Be Virtually Ubiquitous

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Telecommunication and remote-controlled operations are becoming increasingly common in our daily lives. While performing these operations, ideally users would feel as if they were actually present at the remote sites. However, the present commercially available telecommunication and telepresence systems do not provide the sensation of self-presence or self-existence, and hence, users do not get the feeling of being spatially present or that they are directly performing spatial tasks, rather than simply controlling them remotely. Furthermore, these systems do not provide haptic sensation, which is necessary for the direct manipulation of remote operations. The lack of such sensations reduces the sense of realism and makes it more difficult to perform tasks.

In 1980, I proposed the concept of telexistence, which together with the concept of third-generation robotics, was the fundamental principle behind the eight-year, large-scale national Japanese Advanced Robot Technology in Hazardous Environment Project. The project, which began in 1983, established theoretical considerations and the systematic design procedure for telexistence systems.

Since then, experimental hardware systems for telexistence have been developed, and the feasibility of the concept has been demonstrated.[1–5] Two important problems remain to be solved: *mutual telexistence* is a telexistence system that can provide both the sensations of being present (self-presence) and being perceived present (their presence) and is used mainly for communication purposes, whereas *haptic telexistence* adds haptic sensation to the visual and auditory sensations of self-presence and is used mainly for remote operations of real tasks.

This article presents our work on telexistence, in which our aim is to enable human users to have the sensation of being spatially present on site and performing tasks directly. Specifically, we developed a telexistence master-slave system that enables a human user to feel present in a remote environment. This system is a virtual exoskeleton human amplifier, through which a human user can operate a remote avatar robot as if it is his or her own body. That is, the user has the feeling of being inside the robot or wearing it as a garment.

Here, I introduce and explain the recent advancements in telexistence that have partly solved the mutual and haptic telexistence problems. TELESAR II (telexistence surrogate anthropomorphic robot, version II) was the first system to provide the sensations of both self-presence and their presence for communication purposes using retroreflective projection technology (RPT). For remote operation purposes, we have developed the TELESAR V telexistence master-slave system, which can transmit not only visual and auditory sensations, but also haptic sensation. The haptic sensations are conveyed using our proposed principle of haptic primary colors.

Mutual Telexistence

Several commercial products claim to support different forms of telepresence, such as the Teliris telepresence videoconferencing system, Cisco telepresence, Polycom telepresence, Anybots QB telepresence robot, Texai remote presence system, Double telepresence robot, Suitable Beam remote presence system, and VGo robotic telepresence. Yet, although current commercial telepresence robots that are controlled from laptops or intelligent pads can provide a certain sense of their presence on the side of the robot, the remote user has a poor sense of self-presence. As for the sense of their presence, commercial products have problems, such as that the image presented on a display is only a 2D face, which is far from real, and that multi-viewpoint images are not provided. Thus, the same front face is seen even when viewed from the side. An ideal system should provide mutual telexistence, giving

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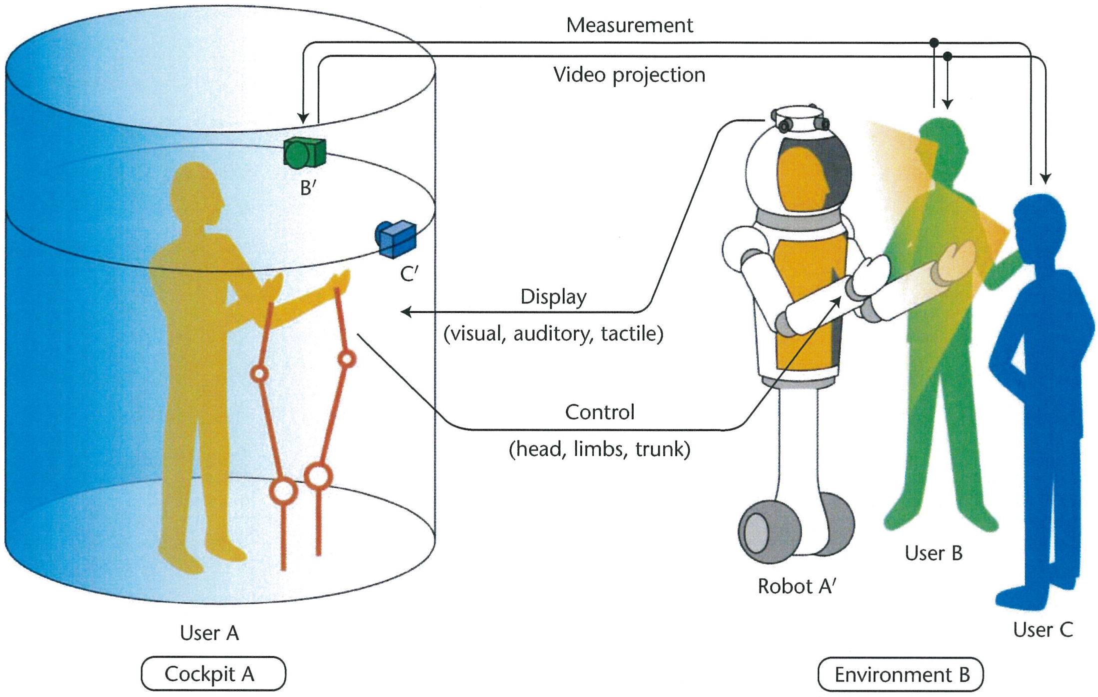


Figure 1. Proposed mutual telexistence system using retroreflective projection technology (RPT). User A can observe remote environment B using an omnistereo camera mounted on surrogate robot A′. The retroreflective material covering robot A′ makes it possible to project images from both cameras B′ and C′ onto it, so users B and C can view the image on robot A′ separately.

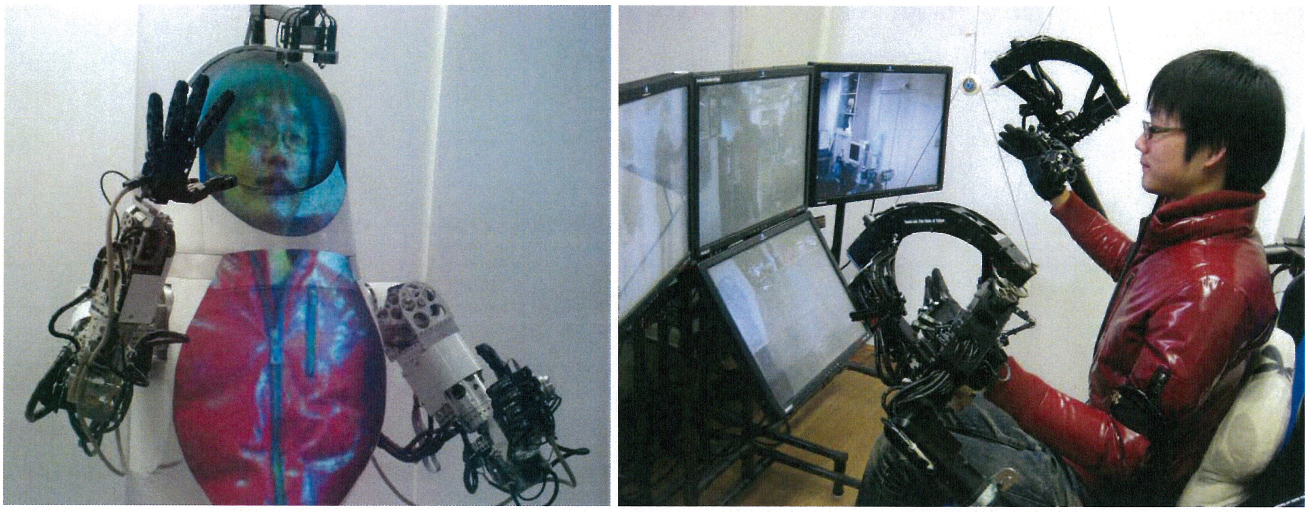
the user a sense being present in the remote environment where his or her surrogate robot exists and, at the same time, creating a sense that the remote user, represented by the surrogate robot, is also present at the remote location. This means the remote user should be seen naturally and simultaneously by several people standing around the surrogate robot. However, almost none of the previous systems provide both the sense of self-presence and the sense of their presence.

Figure 1 shows a conceptual sketch of an ideal mutual telexistence system using a telexistence cockpit and an avatar robot. User A can observe remote environment B using an omnistereo camera mounted on surrogate robot A′. This provides user A with a panoramic stereo view of the remote environment displayed inside the cockpit. User A controls robot A′ using the telexistence master-slave control method. Cameras B′ and C′ mounted on the booth are controlled by the position and orientation of users B and C, respectively, relative to robot A′. To obtain the correct perspective, users B and C can observe different images of user A projected on robot A′ by wearing their own head-mounted projectors (HMPs). Robot A′ is covered with retroreflective material, making it possible to project images from both cameras B′ and C′ onto the same robot while having both images viewed separately by users B and C.

A method for mutual telexistence based on projecting real-time images of the operator onto a surrogate robot using RPT was first proposed in 1999,[6] together with several potential applications such as transparent cockpits.[7] The feasibility of the concept was demonstrated with the construction of experimental mutual telexistence systems in 2004.[8] In 2005, a mutual telexistence master-slave system called TELESAR II was constructed for the Aichi World Exposition.

Figure 2a shows the telexistence surrogate robot TELESAR II. The virtual exoskeleton human amplifier of the remote operator shows his image as if he is inside the robot. Figure 2b shows the operator who is telexisting in the TELESAR II robot. In addition to conventional verbal communication, this master-slave robotics surrogate can perform nonverbal communication such as gestures and handshakes.[9,10] Moreover, a person operating the robot surrogate could be seen naturally and simultaneously by several people standing around the robot at the remote location, so mutual telexistence is attained.

The mobile mutual telexistence system, TELESAR IV, which is equipped with master-slave manipulation capability and an immersive omnidirectional autostereoscopic 3D display with a 360-degree field of view known as TWISTER (telexistence wide-angle immersive stereoscope),[11] was developed in



(a) (b)

Figure 2. Mutual telexistence for spatial interaction. (a) TELESAR II avatar robot and (b) operator at the control.

2010 to further develop a mutual telexistence system toward the ideal form.[12]

Haptic Primary Colors

Humans do not perceive the world as it is. Different physical stimuli give rise to the same sensation in humans and are perceived as identical. A typical example of this fact is human color perception. Humans perceive the light of different spectra as having the same color if the light has the same proportion of the different spectral components. This is because the human retina typically contains three types of color receptors called cone cells or cones, each of which responds to a different range of the color spectrum. Humans respond to light stimuli via 3D sensations, which generally can be modeled as a mixture of the three primary colors (red, green, and blue).

This many-to-one correspondence of elements in mapping from physical properties to psychophysical perception is the key to virtual reality. VR produces the same effect as a real object for a human subject by presenting its virtual entities with this many-to-one correspondence. We have proposed the hypothesis that a cutaneous sensation (that is, one relating to or affecting the skin) also has the same many-to-one correspondence from physical properties to psychophysical perception owing to the physiological constraints of humans. We call this *haptic primary colors*.[13] As Figure 3 shows, we define three spaces: physical, physiological, and psychophysical or perceptual.

In physical space, human skin physically contacts an object, and the interaction continues over time. Physical objects have several surface physical properties such as surface roughness, surface friction, thermal characteristics, and surface elasticity. We hypothesize that at each contact point of the skin, the cutaneous phenomena can be broken down into three components: force $\boldsymbol{f}(t)$, vibration $v(t)$, and temperature $e(t)$. Objects with the same $\boldsymbol{f}(t)$, $v(t)$, and $e(t)$ are perceived as the same, even if their physical properties are different. We measure $\boldsymbol{f}(t)$, $v(t)$, and $e(t)$ at each contact point with sensors that are mounted on the avatar robot's hand and transmit these pieces of information to the human user who controls the avatar robot as his surrogate. We reproduce these pieces of information at the user's hand via haptic displays of force, vibration, and temperature, so that the human user has the sensation that he is touching the object as he moves his hand controlling the avatar robot's hand. We can also synthesize virtual cutaneous sensation by displaying the computer-synthesized $\boldsymbol{f}(t)$, $v(t)$, and $e(t)$ to the human users through the haptic display.

This breakdown into force, vibration, and temperature in physical space is based on the human restriction of sensation in physiological space. Much like the human retina, human skin has limited receptors. In physiological space, cutaneous perception is created through a combination of nerve signals from several types of tactile receptors located below the surface of the skin. If we consider each activated haptic receptor as a sensory base, we should be able to express any given pattern of cutaneous sensation through synthesis by using these bases.

Merkel cells, Ruffini endings, Meissner's corpuscles, and Pacinian corpuscles are activated mainly by pressure, tangential force, low-frequency vibrations, and high-frequency vibrations, respectively. On adding cold receptors (free nerve endings), warmth receptors (free nerve endings), and pain receptors (free nerve endings) to these four vibrotactile haptic sensory bases, we have seven sensory bases in the physiological space.

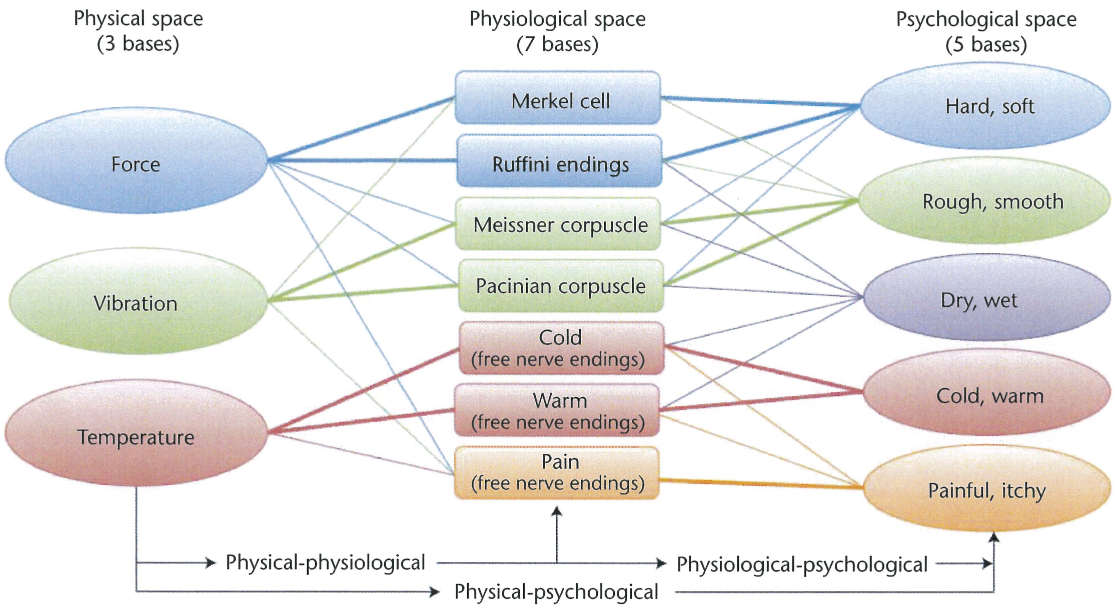


Figure 3. Haptic primary color model. Different physical stimuli give rise to the same sensation in humans and are perceived as identical.

Because all seven receptors are related only to force, vibration, and temperature applied on the skin surface, these three components in the physical space are enough to stimulate each of the seven receptors. Thus, in physical space, we have three haptic "primary colors": force, vibration, and temperature. Theoretically, by combining these three components we can produce any type of cutaneous sensation without the need for any "real" touching of an object.

Telexistence Avatar Robot System: TELESAR V

Conventional telepresence systems provide mostly visual and auditory sensations with only incomplete haptic sensations. TELESAR V, a master-slave robot system for performing full-body movements, was developed in 2011 to realize the concept of haptic telexistence.[14] The TELESAR V master-slave system haptic capabilities were successfully demonstrated at SIGGRAPH in August 2012. TELESAR V can transmit fine haptic sensations during spatial interaction, such as a material's texture and temperature, from an avatar robot's fingers to the human user's fingers,[15] using our proposed principle of haptic primary colors.[13]

The TELESAR V implementation includes a mechanically unconstrained master cockpit and a 53 degrees of freedom (DOF) anthropomorphic slave robot with a high-speed, robust, and full upper body. The system provides an embodiment of our extended body schema, which allows human operators to maintain up-to-date representations of their various body parts in space. A body schema can be used to understand the posture of the remote body and to perform actions as if the remote body is the same as the user's own body. The TELESAR V master-slave system can transmit fine haptic sensations such as the texture and temperature of a material from an avatar robot's fingers to a human user's fingers. Because of this, users can perform tasks dexterously and perceive the robot's body as if it's their own through visual, auditory, and haptic sensations, which provide the fundamental experience of telexistence.

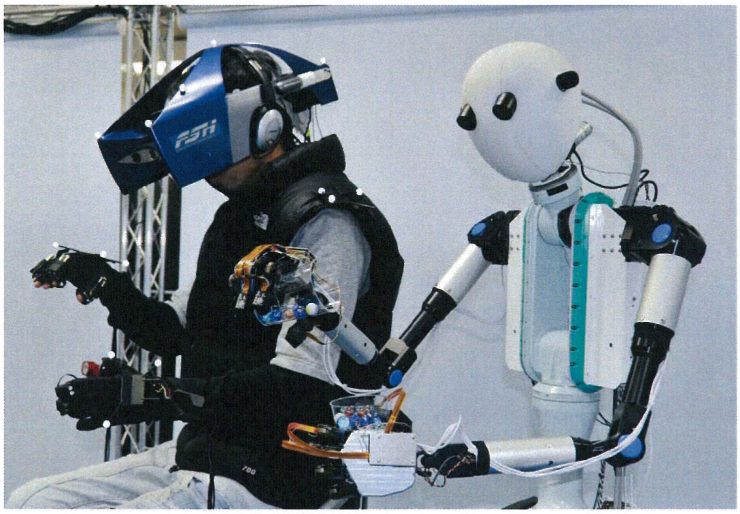


Figure 4. TELESAR V master-slave system. The user can perform tasks dexterously and perceive the robot's body as if it's his or her own through visual, auditory, and haptic sensations.

As shown in Figures 4 and 5, the TELESAR V system consists of a master (local) and a slave (remote). The 53-DOF dexterous robot was developed with a 6-DOF torso, a 3-DOF head, 7-DOF arms, and 15-DOF hands. The robot has full HD cameras (1,920 × 1,080 pixels) for capturing wide-angle stereovision, and stereo microphones are situated on the robot's ears for capturing audio signals from the remote site. The operator's voice is transferred to the remote site and output through a small

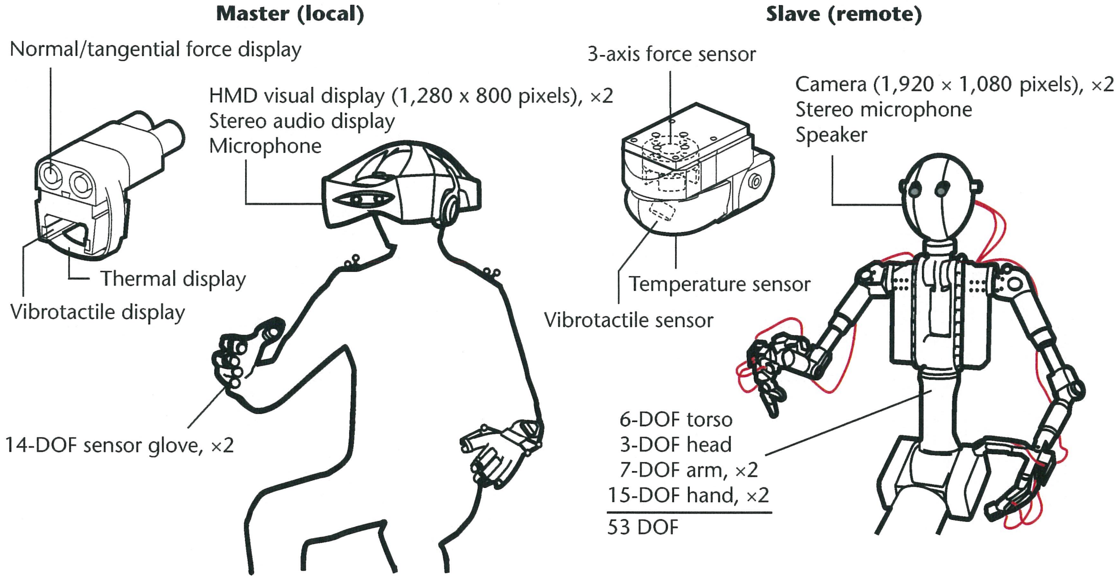


Figure 5. TELESAR V system configuration. The 53-DOF dexterous robot has full HD cameras and stereo microphones for capturing audio-visual signals from the remote site. On the master side, a motion-capturing system and data gloves capture the operator movements.

speaker installed near the robot's mouth area for conventional verbal bidirectional communication. On the master side, the operator's movements are captured with a motion-capturing system (OptiTrack). Finger bending is captured with 14 DOFs using a modified 5DT Data Glove 14.

The haptic transmission system consists of three parts: a haptic sensor, a haptic display, and a processing block. When the haptic sensor touches an object, it obtains haptic information such as contact force, vibration, and temperature based on the haptic primary colors. The haptic display provides haptic stimuli on the user's finger to reproduce the haptic information obtained by the haptic sensor. The processing block connects the haptic sensor with the haptic display and converts the obtained physical data into data that include the physiological haptic perception for reproduction by the haptic display.

First, a force sensor inside the haptic sensor measures the vector force when the haptic sensor touches an object. Then, two motor-belt mechanisms in the haptic display reproduce the vector force on the operator's fingertips. The processing block controls the electrical current drawn by each motor to provide the target torques based on the measured force. As a result, the mechanism reproduces the force sensation when the haptic sensor touches the object.

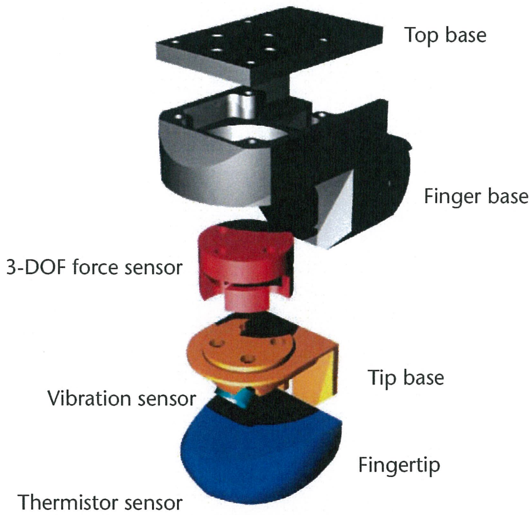


Figure 6. Haptic sensor. The sensor obtains haptic information such as contact force, vibration, and temperature based on the haptic primary colors.

Second, a microphone in the haptic scanner records the sound generated on its surface when the haptic sensor is in contact with an object. Then, a force reactor in the haptic display plays the transmitted sound as a vibration. Because this vibration provides a high-frequency haptic sensation, the information is transmitted without delay.

Third, a thermistor sensor in the haptic sensor measures the surface temperature of the object. A Peltier actuator mounted on the operator's fingertips reproduces the measured temperature. The processing block generates a control signal for the Peltier actuator. The signal is generated based on a proportional-integral-derivative (PID) control loop with feedback from a thermistor located on the Peltier actuator. Figures 6 and 7 show the structures of the haptic sensor and haptic display, respectively.

Figure 8 shows the left hand of TELESAR V robot with the haptic sensors and the haptic displays set in the modified 5DT Data Glove 14.

Figure 9 shows TELESAR V conducting several tasks. The system is able to transmit not only visual and auditory sensations, but also haptic sensations of presence based on data obtained from the haptic sensor.

Toward Telework via Telexistence

Until now, working at home remotely has been limited to communications and/or paper work that transmits audio-visual information and data. It was impossible to carry out physical work at factories or operations at places such as construction sites, healthcare facilities, or hospitals because such activities could not be carried out unless the person in question was actually on site. Telexistence technology can extend the conventional range of remote communications, which transmit only audio-visual senses, to transmit all the physical functions of human beings and thus enable remote work and operations, which were impossible until now.

Given the functionality of an avatar robot, advances in this area could also provide opportunities for elderly and handicapped people. Using the body of a virtual self, such people will no longer be limited by their physical disadvantages. For example, elderly people could augment and enhance their physical functions to surpass the capabilities of their physical bodies by using the avatar's enhanced body and thus can participate in work that makes use of the abundant experience they have gained over a lifetime.

In the future, this technology will also make it possible to dispatch medical and emergency services personnel instantly, allowing them to respond from a safe place during disasters and emergencies. In the same way, medical caregivers, physicians, and experts will be able to access patients in remote areas on a routine basis. In addition, with the creation of new industries such as telexistence tourism, travel, shopping, and leisure, this technology can make the daily lives of citizens more convenient and motivate them to live vigorously. We envision that a healthy and pleasant lifestyle will be realized in a clean and energy-conserving society.

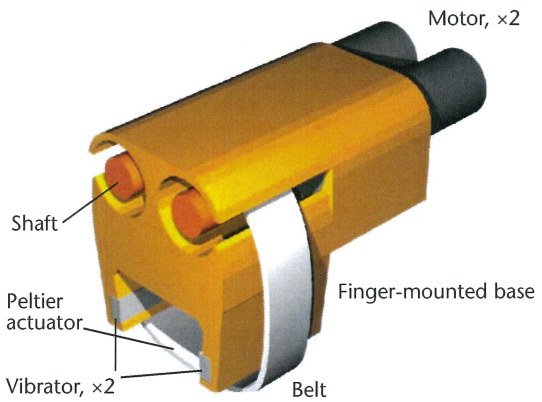


Figure 7. Haptic display. The display provides haptic stimuli on the user's finger to reproduce the haptic information obtained by the haptic sensor.

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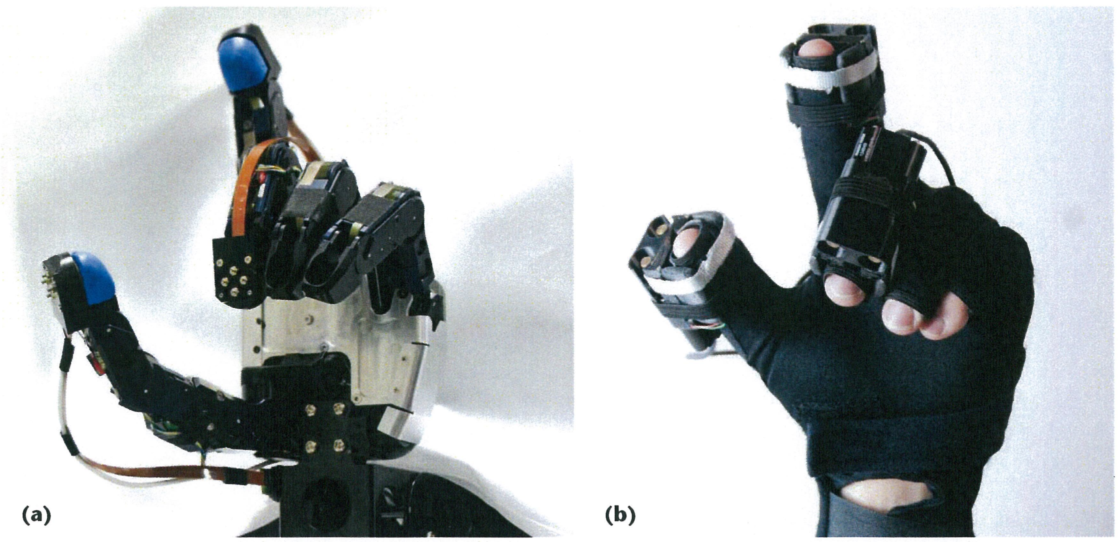

(a) (b)

Figure 8. TELESAR V master and slave hands. (a) Slave hand with haptic sensors and (b) master hand with haptic displays.

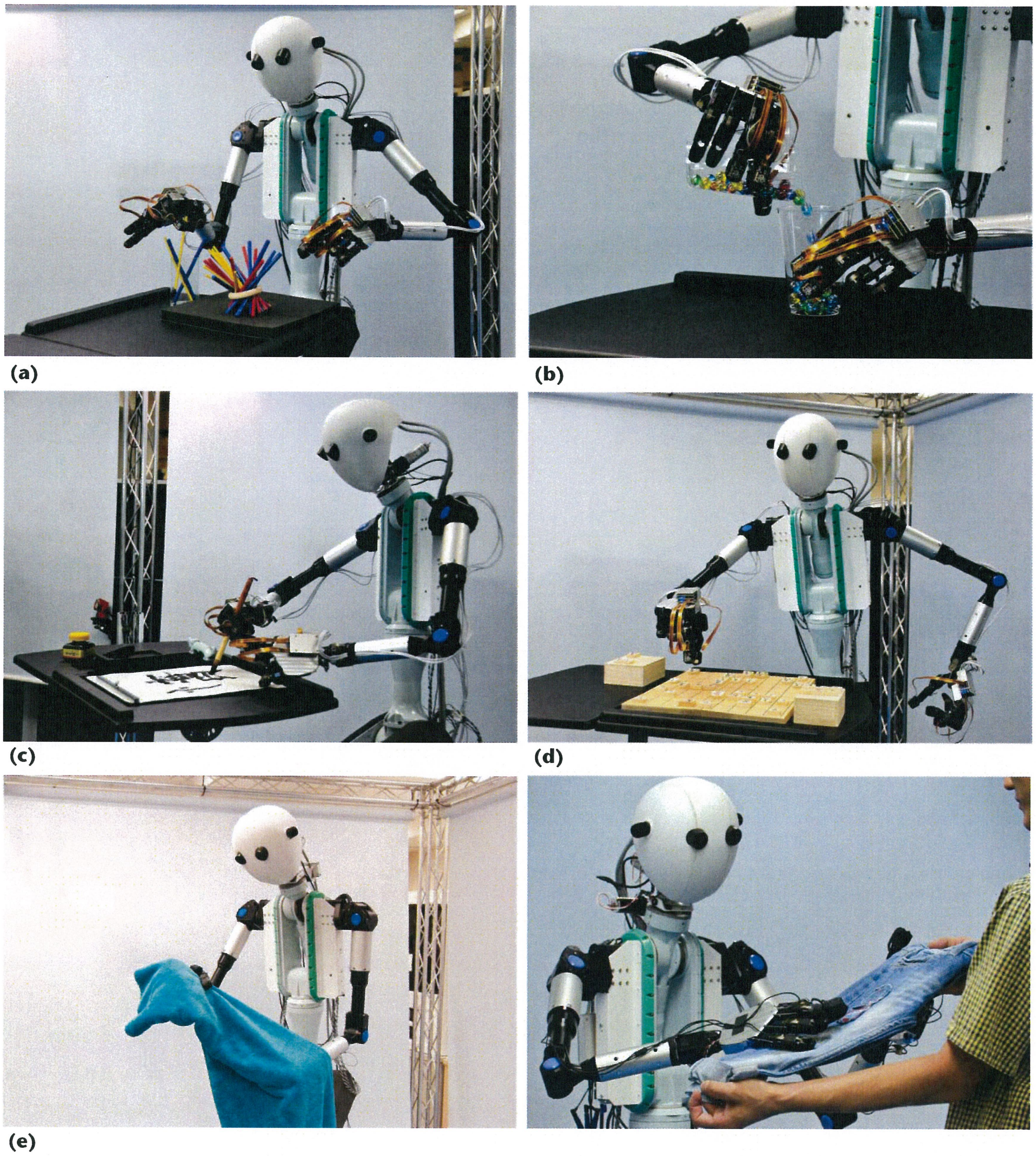

Figure 9. TELESAR V conducting several tasks. (a) Picking up sticks, (b) transferring small balls from one cup to another cup, (c) producing Japanese calligraphy, (d) playing Japanese chess (shogi), and (e) feeling the texture of a cloth.

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