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REVIEW

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Building artificial humans to understand humans

Abstract If we could build an android as a very humanlike robot, how would we humans distinguish a real human from an android? The answer to this question is not so easy. In human–android interaction, we cannot see the internal mechanism of the android, and thus we may simply believe that it is a human. This means that a human can be defined from two perspectives: one by organic mechanism and the other by appearance. Further, the current rapid progress in artificial organs makes this distinction confusing. The approach discussed in this article is to create artificial humans with humanlike appearances. The developed artificial humans, an android and a geminoid, can be used to improve understanding of humans through psychological and cognitive tests conducted using the artificial humans. We call this new approach to understanding humans android science.

Key words Robot · Android · Geminoid · Cognitive science

Introduction

Why are people attracted to humanoid robots and androids? The answer is simple: because human beings are attuned to understand or interpret human expressions and behaviors, especially those that exist in their surroundings. As they grow, infants, who are supposedly born with the ability to discriminate various types of stimuli, gradually adapt and fine tune their interpretations of detailed social clues from other people's voices, languages, facial expressions, or behaviors.[1] Perhaps because of this functionality of nature and nurture, people have a strong tendency to anthropomorphize nearly everything they encounter, including computers and robots. In other words, when we see PCs or robots, some automatic process starts running inside us that tries to interpret them as human. The media equation theory[2] was the first to explicitly articulate this tendency within us. Since then, researchers have been pursuing the key element that make people feel more comfortable with computers or to create an easier and more intuitive interface to various information devices. This pursuit has also begun spreading in the field of robotics. Recently, researchers' interests in robotics have been shifting from traditional studies on navigation and manipulation to human–robot interactions. A number of research projects have investigated how people respond to robot behaviors and how robots should behave so that people can easily understand them.[3–5] Many insights from developmental or cognitive psychologies have been implemented and examined to see how they affect the human response or whether they help robots produce smooth and natural communication with humans.

However, human–robot interaction studies have neglected one issue: the "appearance versus behavior" problem. We empirically know that appearance, one of the most significant elements in communication, is a crucial factor in the evaluation of interaction (see Fig. 1). The interactive robots developed so far have resulted in very mechanical outcomes and clearly *are* robots. Researchers have tried to make such interactive robots more humanoid by equipping them with heads, eyes, or hands so that their appearance more closely resembles human beings, thus enabling them to make such analogous human movements or gestures as staring, pointing, and so on. Functionality was considered the primary concern in improving communication with humans. In this manner, many studies have compared robots with different behaviors. Thus far, scant attention has been paid to the appearance of robots. Although there are many empirical discussions on such very simple static robots as dolls, the design of a robot's appearance, particu-

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Fig. 1. Three categories of humanlike robots: humanoid robot Eveliee P1 (*left*: developed by Osaka University), android Repliee Q2 (*middle*: developed by Osaka University and Kokoro Corporation), and Geminoid HI-1 (*right*: developed by ATR Intelligent Robotics and Communication Laboratories)

larly to increase its human likeness, has always been the role of industrial designers; it has seldom been a field of study. This is a serious problem for developing and evaluating interactive robots. Recent neuroimaging studies have shown that the activation of certain brain areas does not occur when the observed actions are performed by nonhuman agents.[6,7] Appearance and behavior are tightly coupled, and concern is high that evaluation results might be affected by appearance.

In this article, we introduce android science, an interdisciplinary research framework that combines two approaches, one in robotics for constructing very humanlike robots and androids, and the other in cognitive science that uses androids to explore human nature. Here androids serve as a platform to directly exchange insights from the two domains. To proceed with this new framework, several androids have been developed so far. The developments of android systems and several results obtained are described. At this stage, however, we encountered serious issues that sparked the development of a new category of robot called a geminoid. The concept and the development of the first prototype geminoid are described. Preliminary findings to date and future directions with geminoids are also discussed.

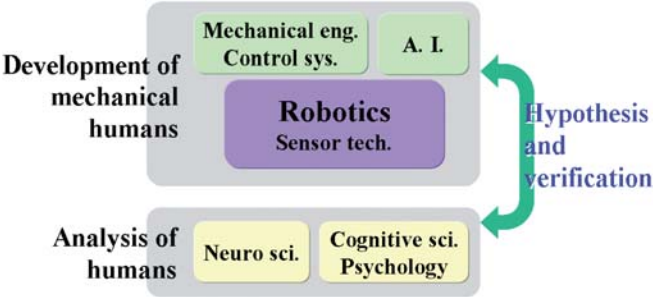

Fig. 2. Framework of android science. *AI*, artificial intelligence

Android science

Current robotics research uses various findings from the field of cognitive science, especially in the area of human–robot interaction, in an attempt to adopt findings from human–human interactions to make robots that people can easily communicate with. At the same time, cognitive science researchers have also begun to utilize robots. As research fields extend to more complex, higher-level human functions such as seeking the neural basis of social skills,[8] expectations will rise for robots to function as easily controlled apparatuses with communicative ability. However, the contribution from robotics to cognitive science has not been adequate because the appearance and behavior of current robots cannot be separately handled. Since traditional robots look quite mechanical and look very different from human beings, the effect of their appearance may be too strong to ignore. As a result, researchers cannot clarify whether a specific finding reflects the robot's appearance, its movement, or a combination of both.

We expect to solve this problem using an android whose appearance and behavior closely resemble those of humans. The same thing is also an issue in robotics research, since it is difficult to clearly distinguish whether the cues pertain solely to robot behaviors. An objective, quantitative means of measuring the effect of appearance is required.

Androids are robots whose behavior and appearance are highly anthropomorphized. Developing androids requires contributions from both robotics and cognitive science. To realize a more humanlike android, knowledge from human sciences is also necessary. At the same time, cognitive science researchers can exploit androids for verifying hypotheses in understanding human nature. This new, bidirectional, interdisciplinary research framework is called android science.[9] Under this framework, androids enable us to directly share knowledge between the development of androids in engineering and the understanding of humans in cognitive science (Fig. 2).

The major robotics issue in constructing androids is the development of humanlike appearance, movements, and perception functions. On the other hand, one issue in cognitive science is "conscious and unconscious recognition." The goal of android science is to realize a humanlike robot and to find the essential factors for representing human likeness. How can we define human likeness? Further, how do we perceive human likeness? It is common knowledge that humans have conscious and unconscious recognition. When we observe objects, various modules are activated in our brains. Each of them matches the input sensory data with human models, and then they affect reactions. A typical example is that even if we recognize a robot as an android, we react to it as a human. This issue is fundamental both for engineering and scientific approaches. It will serve as an evaluation criterion in android development and will provide clues to understanding the human brain's mechanism of recognition.

So far, several androids have been developed. Repliee Q2, the latest android,[9] is shown in the middle of Fig. 1. Forty-two pneumatic actuators are embedded in the android's upper torso, allowing it to move smoothly and quietly. Tactile sensors, which are also embedded under its skin, are connected to sensors in its environment, such as omnidirectional cameras, microphone arrays, and floor sensors. Using these sensory inputs, the autonomous program installed in the android can make smooth, natural interactions with people near it.

Even though these androids enabled us to conduct a variety of cognitive experiments, they are still quite limited. The bottleneck in interaction with humans is its lack of ability to perform long-term conversation. Unfortunately, since current AI technology for developing humanlike brains is limited, we cannot expect humanlike conversation with robots. When meeting humanoid robots, people usually expect humanlike conversation with them. However, the technology greatly lags behind this expectation. AI progress takes time, and AI that can achieve humanlike conversation is our final goal in robotics. To arrive at this final goal, we need to use currently available technologies and understand deeply what a human being is. Our solution to this problem is to integrate android and teleoperation technologies.

Developing androids

To date, several androids have been developed. Figure 3 shows two androids: Repliee R1, the first android prototype, and Repliee Q2, the latest android.[9] As stated before, engineering issues in creating androids involve the development of humanlike appearance, movements, and perception. Here we describe our approach to resolving each of these issues.

Humanlike appearance

The main difference between robots and androids is in their appearance. In order to create a very humanlike robot, we began by copying the surface of human skin.

First, body part molds were made from a real human using the shape-memory form used by dentists. Then plaster human part models were made from the molds. A full-body model was constructed by connecting these plaster models. Again, a mold for the full-body model was made from the plaster model and a clay model was made by using the mold. Here, professionals in formative art modified the clay model in order to recover the details of skin texture. The human model loses its form in the first molding process because human skin is soft. After that modification, a plaster full-body mold was made from the modified clay model, and then a silicone full-body model was made from that plaster mold. This silicone model is maintained as a master model.

Using this master model, silicone skin for the entire body was made. The thickness of the silicone skin is 5 mm in our

Fig. 3. The first android; Repliee R1 (*left*: developed by Osaka University), and the latest android, Repliee Q2 (*right*: developed by Osaka University and Kokoro Corporation)

current version. The mechanical parts, motors, and sensors were covered with polyurethane and the produced silicone skin. As shown in the figure, the details are so finely represented that they cannot be distinguished from those of human beings in photographs.

Our current technology for replicating the human figure as an android has reached a fine degree of reality. It is, however, still not perfect. One issue is the detail of the wetness of the eyes. The eye is the body part to which human observers become most sensitive. When confronted with a human face, a person first looks at the eyes. Although the android has eye-related mechanisms, such as blinking or making saccade movements, and the eyeballs are near-perfect copies of those of a human, we still become aware of the differences from a real human. Actually, producing a wet surface for the eye and replicating the outer corners using silicone are difficult tasks, so further improvements are needed in these areas.

Other issues are the flexibility and robustness of the skin material. The silicone used in the current manufacturing process is sufficient for representing the texture of the skin; however, it loses flexibility after 1 or 2 years, and its elasticity is insufficient for adapting to large joint movements.

Humanlike movements

Very humanlike movement is another important factor in developing androids. Even if androids look indistinguishable from humans as static figures, without appropriate movements, they can be easily identified as artificial.

To achieve highly humanlike movement, we found that a child android was too small to embed the number of actuators required, which led to the development of an adult android. The right half of Fig. 3 shows our latest adult android. This android, named Repliee Q2, contains 42 pneumatic actuators in the upper torso. The positions of the actuators were determined by analyzing real human movements using a precise three-dimensional (3D) motion tracker. With these actuators, both unconscious movements, such as breathing in the chest, and conscious large movements, such as head or arm movements, can be generated. Furthermore, the android is able to generate the facial expressions that are important for interacting with humans. Figure 4 shows some of the facial expressions generated by the android. In order to generate a smooth, humanlike expression, 13 of the 42 actuators are embedded in the head.

We decided to use pneumatic actuators for the androids, instead of the DC motors used in most robots. The use of a pneumatic actuator provides several benefits. First, they are almost silent, producing a much more humanlike sound. DC servomotors require reduction gears, which generate nonhuman, very robotic sounds. Second, the reaction of the android to external force becomes very natural with the pneumatic damper. If we use DC servomotors with reduction gears, sophisticated compliance control is required to obtain the same effect. This is also important for ensuring safety in interactions with the android.

On the other hand, the weakness of pneumatic actuators is that they require a large and powerful air compressor. Because of this requirement, the current android cannot walk. For wider applications, we need to develop new electric actuators that have similar properties to the pneumatic actuators.

The next issue is how to control the 42 air servoactuators used to achieve very human-like movements. The simplest approach is to directly send angular information to each joint. However, as the number of actuators in the android is relatively large, this takes a long time. Another difficulty is that the skin movement does not simply correspond to the joint movement. For example, the android has more than five actuators around the shoulder for generating humanlike shoulder movements, with the skin moving and stretching according to the actuator motions. Already, we have developed methods such as using Perlin noise[10] to generate smooth movements and we have used a neural network to obtain mapping between the skin surface and

Fig. 4. Facial expressions generated by android Repliee Q2

Fig. 5. Replicating human motions with the android

actuator movements. There still remain some issues, such as the limited speed of android movement due to the nature of the pneumatic damper. To achieve quicker and more humanlike behavior, speed and torque controls are required in our future studies.

After obtaining an efficient method for controlling the android, the next step is the implementation of humanlike motions. A straightforward approach to this challenge is to imitate real human motions in synchronization with the android's master. By attaching 3D motion tracker markers on both the android and the master, the android can automatically follow human motions (Fig. 5).

This work is still in progress, but interesting issues have arisen with respect to this kind of imitation. Imitation by the android means representation of complicated human shapes and motions in the parameter space of the actuators. Although the android has a relatively large number of actuators compared to other robots, the number is still far smaller than that of a human. Thus, the effect of data size reduction is significant. By carefully examining this parameter space and mapping, we may find important properties of human body movements. More concretely, we expect to develop a hierarchical representation of human body movements that consists of two or more layers, such as small unconscious movements and large conscious movements. With this hierarchical representation, we can expect to achieve more flexibility in android behavior control.

Humanlike perception

Androids require humanlike perceptual abilities in addition to humanlike appearance and movements. This problem has been tackled in the fields of computer vision and pattern recognition in rather controlled environments. However, the problem becomes extremely difficult when applied to robots in real-world situations, since vision and audition become unstable and noisy.

Ubiquitous/distributed sensor systems solve this problem. The idea is to recognize the environment and human activities by using many distributed cameras, microphones, infrared motion sensors, floor sensors, and Identification (ID) tag readers in the environment (Fig. 6).

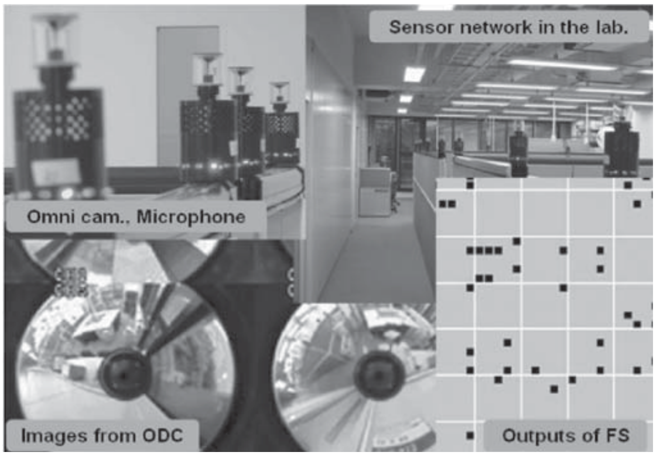

Fig. 6. Distributed sensor system. *ODC*, omnidirectional camera; *FS*, floor sensor

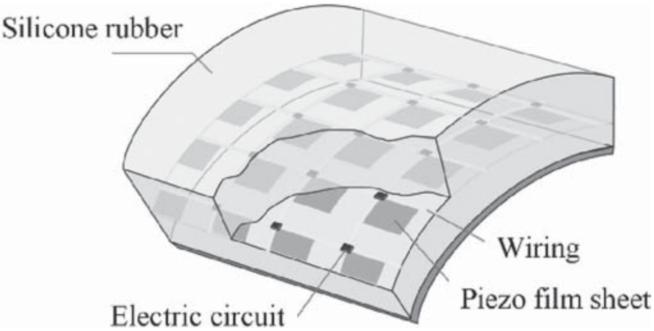

Fig. 7. Skin sensors

We developed distributed vision systems[11] and distributed audition systems[12] in our previous work. To solve the present problem, these developments must be integrated and extended. The omnidirectional cameras observe humans from multiple viewing points and robustly recognize their behaviors.[13] The microphones catch the human voice by forming virtual sound beams. The floor sensors, which cover the entire space, reliably detect the footsteps of humans.

The only sensors that should be installed in the robot are skins sensors. Soft and sensitive skin sensors are important, particularly for interactive robots. However, there has not been much work done in this area in previous robotics research. We are now focusing on its importance in developing original sensors. Our sensors are made by combining silicone skin and Piezo films (Fig. 7). This sensor detects pressure by bending the Piezo films. Furthermore, it can detect very near human presence from static electricity by increasing the sensitivity, i.e., it can perceive a signal that a human being is there.

These technologies for very humanlike appearance, behavior, and perception enable us to develop feasible androids. These androids have undergone various cognitive tests, but this work is still limited. The bottleneck is long-term conversation in interaction. Unfortunately, current artificial intelligence (AI) technology for developing humanlike brains has only a limited ability, and thus we cannot expect humanlike conversation with robots. When we meet humanoid robots, we usually expect to have humanlike conversation with them. However, the technology is very far behind this expectation. Progress in AI takes time, and this is actually our final goal in robotics. In order to arrive at this final goal, we need to use the technologies available today and, moreover, we need to truly understand what a human is. Our solution to this problem is to integrate android and teleoperation technologies.

Geminoid

We have developed a geminoid, a new category of robot, to overcome the bottleneck issue. We coined the term geminoid from the Latin "geminus," meaning "twin" or "double," and added "oides," which indicates similarity or being a twin. As the name suggests, a geminoid is a robot that will work as a duplicate of an existing person. It appears and behaves as a person and is connected to the person by a computer network. Geminoids extend the applicable field of android science. Androids are designed for studying human nature in general. With geminoids, we can study such personal aspects as presence or personality traits, tracing their origins and implementation into robots. Figure 8 shows the robotic part of HI-1, the first geminoid prototype. Geminoids have the capabilities discussed in the following sections:

Appearance and behavior highly similar to an existing person

The appearance of a geminoid is based on an existing person and does not depend on the imagination of designers. Its movements can be produced or evaluated simply by referring to the original person. The existence of a real person analogous to the robot enables easy comparison studies. Moreover, if a researcher is used as the original, we can expect that individual to offer meaningful insights into the experiments, which are especially important at the very first stage of a new field of study when beginning from established research methodologies.

Teleoperation (remote control)

Since geminoids are equipped with teleoperation functionality, they are not only driven by an autonomous program. By introducing manual control, the limitations in current AI technologies can be avoided, enabling long-term, intelligent conversational human–robot interaction experiments. This feature also enables various studies on human characteristics by separating "body" and "mind." In geminoids, the operator (mind) can be easily exchanged, while the robot (body) remains the same. Also, the strength of connection, or what kind of information is transmitted between the body and mind, can be easily reconfigured. This is especially important when taking a top-down approach that adds/deletes elements from a person to discover the critical elements that comprise human characteristics. Before geminoids, this was impossible.

System overview

The current geminoid prototype, HI-1, consists of roughly three elements: a robot, a central controlling server (geminoid server), and a teleoperation interface (Fig. 9).

A robot that resembles a living person

The robotic element has essentially identical structure to previous androids.[9] However, efforts are concentrated on making a robot that appears to be a copy of the original person, not just to resemble a living person. Silicone skin was molded by a cast taken from the original person; shape adjustments and skin textures were painted manually based on magnetic resonance imaging Magnetic Resonance Imaging (MRI) scans and photographs. Fifty pneumatic actuators drive the robot to generate smooth and quiet movements, which are important attributes when interacting with humans. The allocation of actuators was decided so

Fig. 8. Geminoid HI-1 and its human source

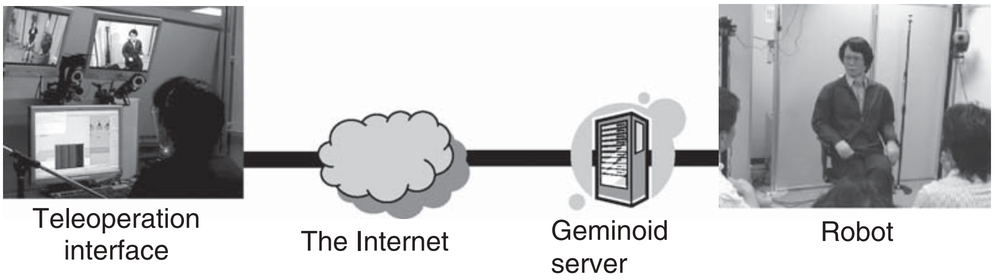

Fig. 9. Overview of the geminoid system

Fig. 10. Teleoperation interface

that the resulting robot could effectively make the necessary movements for human interaction and simultaneously express the original person's personality traits. Among the 50 actuators, 13 were embedded in the face, 15 in the torso, and the remaining 22 move the arms and legs. The softness of the silicone skin and the compliant nature of the pneumatic actuators also provide safety while interacting with humans. Since this prototype was aimed at interaction experiments, it lacks the capability to walk around; it always remains seated. Figure 8 shows the resulting robot (right) alongside the original person, Dr. Ishiguro (one of the authors).

Teleoperation interface

Figure 10 shows the teleoperation interface prototype. Two monitors show the controlled robot and its surroundings, and microphones and a headphone are used to capture and transmit conversation. The captured sounds are encoded and transmitted to the geminoid server by IP links from the interface to the robot and vice versa. The operator's lip corner positions are measured by an infrared motion capturing system in real time, converted to motion commands, and sent to the geminoid server by the network. This enables the operator to implicitly generate suitable lip movement on the robot while speaking. However, compared to the large number of human facial muscles used for speech, the current robot has only a limited number of actuators in its face. Also, the response speed is much slower, partially due to the nature of the pneumatic actuators. Thus, simple transmission and playback of the operator's lip movements would not result in sufficient, natural robot motion. To overcome this issue, measured lip movements are currently transformed into control commands using heuristics obtained through observation of the original person's actual lip movements.

The operator can also explicitly send commands to control robot behavior using a simple GUI interface. Several selected movements, such as nodding, contradicting, or staring in a certain direction can be specified by a single mouse click. This relatively simple interface was prepared because the robot has 50 degrees of freedom, which makes it one of the world's most complex robots, and it is basically impossible to manipulate the system manually in real time. A simple, intuitive interface is necessary so that the operator can concentrate on interaction and not on robot manipulation. Despite its simplicity, by cooperating with the geminoid server, this interface enables the operator to generate natural humanlike motions in the robot.

Geminoid server

The geminoid server receives robot control commands and sound data from the remote controlling interface, adjusts and merges inputs, and sends and receives primitive controlling commands to and from the robot hardware. Figure 6 shows the data flow in the geminoid system. The geminoid server also maintains the state of human–robot interaction and generates autonomous or unconscious movements for the robot. As described above, as a robot's features become more humanlike, its behavior should also become suitably sophisticated to retain a "natural" look.[14]

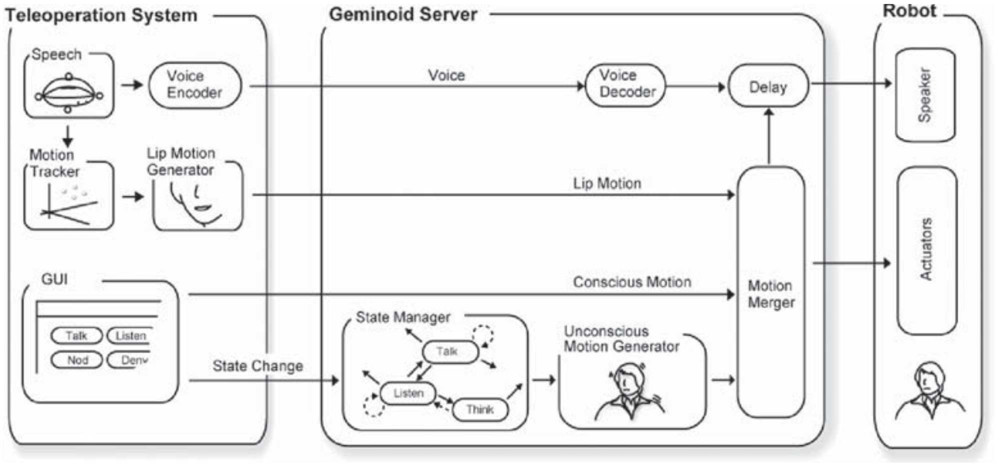

Fig. 11. Data flow in the geminoid system

One thing that can be seen in every human being, and that most robots lack, are the slight body movements caused by the autonomous system, such as breathing or blinking. To increase the robot's naturalness, the geminoid server emulates the human autonomous system and automatically generates these micro-movements, depending on the state of interaction each time. When the robot is "speaking," it makes different micromovements than when "listening" to others. Such automatic robot motions, generated without the operator's explicit orders, are merged and adjusted with conscious operation commands from the teleoperation interface (Fig. 11). In addition, the geminoid server gives the transmitted sounds specific delays, taking into account the transmission delay/jitter and the start-up delay of the pneumatic actuators. This adjustment serves to synchronize lip movements and speech, thus enhancing the naturalness of geminoid movement.

Experiences with the geminoid prototype

The first geminoid prototype, HI-1, was completed and press-released in July 2006. Since then, much work has been carried out, including interactions with lab members and experimental subjects. Also, the geminoid was demonstrated to a number of visitors and reporters. During these operations, we encountered several interesting phenomena. Here are some observations made by the geminoid operator:

- When I (Hiroshi Ishiguro, the person on whom the geminoid prototype was based) first saw HI-1 sitting still, it was like looking in a mirror. However, when it began moving, it looked like somebody else, and I could not recognize it as myself. This was strange, since we copied my movements to HI-1, and others who know me well say the robot accurately represents my characteristics. This means that we do not objectively recognize our unconscious movements ourselves.
- While operating HI-1 with the operation interface, I found myself unconsciously adapting my movements to the geminoid's movements. The current geminoid cannot move as freely as I can. I felt that, not only the geminoid but also my own body was restricted to the movements that HI-1 can make.
- In less than 5 min both the visitors and I could quickly adapt to conversation through the geminoid. The visitors recognized and accepted the geminoid as me while we were talking to each other.
- When a visitor touched HI-1, especially around its face, I got a strong feeling of being touched myself. This is strange, as the system currently provides no tactile feedback. Just by watching the monitors and interacting with visitors, I got this feeling.

We also asked the visitors how they felt when interacting through the geminoid. Most said that when they saw HI-1 for the very first time, they thought that somebody (or Dr. Ishiguro, if familiar with him) was waiting there. After taking a closer look, they soon realized that HI-1 was a robot and began to have some weird and nervous feelings. But shortly after having a conversation through the geminoid, they found themselves concentrating on the interaction, and soon the strange feelings vanished. Most of the visitors were non-researchers unfamiliar with robots of any kind.

Does this mean that the geminoid has overcome the "uncanny valley"? Before talking through the geminoid, the initial response of the visitors seemingly resembled the reactions seen with previous androids: even though at the very first moment they could not recognize the android as artificial, they nevertheless soon became nervous while being with the android. Is intelligence or long-term interaction a crucial factor in overcoming the valley and arriving at an area of natural humanness?

We certainly need objective means to measure how people feel about geminoids and other types of robots. In a previous android study, Minato et al. found that gaze fixation revealed criteria about the naturalness of robots.[14] Recent studies have shown different human responses and reactions to natural or artificial stimuli of the same nature. Perani et al. showed that different brain regions are activated while watching human or computer graphic arms movements.[6] Kilner et al. showed that body movement entrainment occurs when watching human motions, but not with robot motions.[15] By examining these findings with geminoids, we may be able to find some concrete measurements of human likeness and approach the "appearance versus behavior" issue.

Perhaps HI-1 was recognized as a sort of communication device, similar to a telephone or a video phone. Recent studies have suggested a distinction in brain processes that discriminate between people appearing in videos and existing persons appearing live.[16] While attending video conferences or talking by cellular phone, however, we often experience the feeling that something is missing compared to a face-to-face meeting. What is missing here? Is there an objective means to measure and capture this element? Can we ever implement this in robots?

Summary and further issues

In developing the geminoid, our purpose was to study *sonzai-kan*, or human presence, by extending the framework of android science. The scientific aspect must answer questions about how humans recognize human existence/presence. The technological aspect must realize a teleoperated android that works on behalf of the person remotely accessing it. This will be a practical networked robot realized by integrating the robot with the Internet. The following are our current challenges.

Teleoperation technologies for complex humanlike robots. Methods must be studied to teleoperate the geminoid to convey existence/presence, which is much more complex than traditional teleoperation for mobile and industrial robots. We are studying a method to autonomously control an android by transferring the motions of the operator measured by a motion capturing system. We are also developing methods to autonomously control eye gaze and humanlike small and large movements.

Synchronization between speech sent by the teleoperation system and body movements. The most important technology for the teleoperation system is synchronization between speech and lip movements. We are investigating how to produce natural behaviors during speech. This problem is extended to other modalities, such as head and arm movements. Further, we are studying the effects of nonverbal communication by investigating not only synchronization of speech and lip movements but also facial expressions, head, and even whole body movements.

Psychological test for human existence/presence. We are studying the effect of transmitting *sonzai-kan* from remote places, such as in a meeting in which a geminoid participates instead of the actual person. Moreover, we are interested in studying existence/presence through cognitive and psychological experiments. For example, we are studying whether the android can represent the authority of the person himself by comparing the person and the android.

Applications. Although being developed as a piece of research apparatus, the nature of geminoids can allow us to extend the use of robots in the real world. The teleoperated, semi-autonomous facility of geminoids allows them to be used as substitutes for clerks, for example, that can be controlled by human operators only when nontypical responses are required. Since in most cases an autonomous AI response will be sufficient, a few operators will be able to control hundreds of geminoids. Also because their appearance and behavior closely resembles humans, in the future geminoids should be the ultimate interface device.

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