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Development and Evaluation of an Interactive Humanoid Robot "Robovie"

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Abstract

In this paper, we report about a new interaction-oriented robot, which communicates with humans and will participate in human society as our partner. For realizing such a robot, we have started a new collaborative work between cognitive science and robotics. In the way of robotics, we have developed a humanoid robot named "Robovie" that has enough physical expression ability. On the other hand, through cognitive experiments, we obtained important ideas about the robot's body property. To incorporate these ideas, we have developed software architecture and implemented autonomous interactive behaviors to the robot. Further, we have evaluated the robot's performance of the interactive behaviors through psychological experiments. The experiments reveled how humans recognize the robot.

1. Introduction

There are two research directions in robotics; one is to develop task-oriented robots that work in limited environments, and the other is to develop interaction-oriented robots that communicate with humans and will participate in human society. Industrial and pet robots are the former ones. They work in factories and limited areas in houses with particular tasks such as assembling industrial parts, behaving like animals, and so on. On the other hand, the purpose of the interaction-oriented robots that we are developing is not to execute particular tasks. We are trying to develop a robot that exists as our partner in our daily life. These robots will be a new information infrastructure for communication.

Regarding the robots that interact with humans, there are many researches: conveying intentionality through facial expressions and behavior [1], mimicking of human body motions [2], developing a mentally-commitment robot [3] and so forth. These robots, however, lack physical expression ability. For example: some of them have only heads, some look like animals, and some cannot speak. We developed a robot named "Robovie" that has enough physical expression ability. It can generate almost all human-like behaviors required for human-robot communication, and interacts with humans by using rich sensory information.

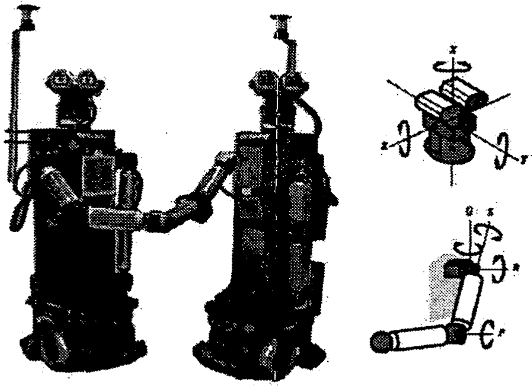

Fig. 1: Robovie – it has enough physical expression ability

For making the best use of the physical expression ability, we have started a new collaborative work between cognitive science and robotics. Cognitive science, especially on the ideas about the practical use of the body properties for communication, helps to design more effective robot behaviors. On the other hand, the developed robot that has enough physical expression ability can be used for verifying theories of cognitive science. Then, to incorporate the ideas from cognitive science, we considered new software architecture. It enables easy development and rich human-robot interaction. We believe this unique interdisciplinary relationship enables us to develop the new type of robot.

Further, we intended to evaluate the performance of the implemented interactive behaviors. About the task-oriented robots, we can evaluate their performance with physical measures such as speed and accuracy. These measures help us to improve the performance. Similarly, we need to apply psychological measures for the interaction-oriented robots. Because, the performance of these robots that interact with humans is discussed along with how they influence humans. For realizing the interaction-oriented robots, we believe it is important and necessary to repeatedly improve both the software architecture and the measurement method.

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About the evaluations of human-robot interaction, several works have been performed so far with basic psychological questionnaires. Nakata and his colleagues analyzed the effects of expressing emotions and intention [4]. Ogata and his colleagues studied emotional communication by evaluating the impressions of the robot [5]. In addition to these direct evaluations, we adopted unobtrusive measures. The unobtrusive measures are used in psychological researches [6], and they have the merit that measurement does not obstruct experiments. Mizoguchi and his colleagues have already employed spatial distance between humans and a robot [7]. Besides the spatial distance, we focused on humans' touching and communicative behaviors toward a robot. These unobtrusive measures enable us to evaluate dynamic aspect of the interaction, whereas these questionnaire methods only reveal static aspect after the interaction.

In this paper, we explain the development of the interactive humanoid robot "Robovie" through the interdisciplinary approach, and then report experiments to evaluate the implemented behaviors. The results proved enough interaction ability of the robot and behaviors. At the same time, we consider the results indicate how humans regard such an interactive humanoid robot.

2. Interactive humanoid robot "Robovie"

2.1. Hardware

We have developed a robot named "Robovie" shown in Fig. 1. The robot that has a human-like appearance is designed for communication with humans. Like a human, it has various sensors, such as vision, sense of touch, audition and so on. With the human-like body and sensors, the robot performs meaningful interactive behaviors for humans.

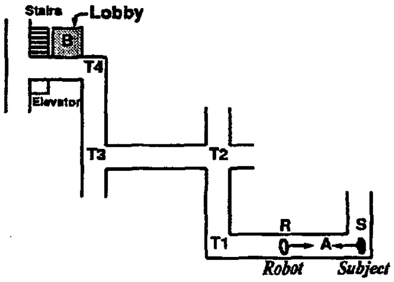

Fig. 2: The structure of the environment for an experiment in cognitive science

Fig. 3: Scenes of an experiment in cognitive science — Emergence of mutual entrained gestures (synchronous body movement to the robot's gesture) —

The size is important as an interactive robot. Not to give an awful impression to humans, we have decided the size as 120 cm, which is same as a junior school student. The diameter is 40 cm and the weight is about 40 kg. The robot has two arms (4*2 DOF), a head (3 DOF), two eyes (2*2 DOF for gaze control), and a mobile platform (2 driving wheels and 1 free wheel). The robot farther has various sensors, 16 skin sensors covering the major parts of the robot, 10 tactile sensors around the mobile platform, an omnidirectional vision sensor, 2 microphones to listen human voices, and 24 ultra-sonic sensors for detecting obstacles. The eye has pan-tilt mechanism with direct-drive motors, and they are used for stereo vision and gazing control. The skin sensors are important for realizing interactive behaviors. We have developed a sensitive skin sensors using pressure sensitive conductivity rubber. Another important point in the design is the battery life. This robot can work 4 hours and charges the battery by autonomously looking for battery-charging stations. With the actuators and sensors, the robot can generate enough behaviors required for communication with humans.

Robovie is a self-contained autonomous robot. It has a Pentium III PC on board for processing sensory data and generating behaviors. The operating system is Linux. Since the Pentium III PC is sufficiently fast and Robovie does not require precise real-time controls like a legged robot, Linux is the best solution for easy and quick development of Robovie's software modules.

2.2. Knowledge from Cognitive Science

With this robot, we performed experiments on human-robot communication in cognitive science (fully reported in [8]). We briefly explain one of the experiments in cognitive science and obtained ideas about robot's body property.

Cognitive Experiment using Robovie

Mutual entrained gestures are important for smooth communications between a robot and a human. We have performed an experiment to ensure it. We focused on the interaction between a subject (human who interacts with the robot in the experiment) and the robot while it teaches a route direction to the subject. Fig. 2 displays the environment and the settings of the experiment. By using several different gestures of the robot in the teaching, the relationships between the emergence of the subject's entrained gestures and the level of the understanding of the robot's utterance was investigated.

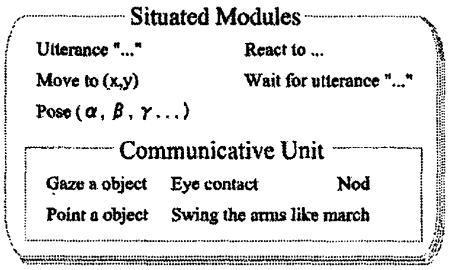

Fig. 4: Situated modules and Communicative unit

The experiments consist of the following phases:

1. The subject and the robot move from S to A and from R to A, respectively.
2. The subject asks a route to the lobby (B). The robot says, "Go forward, turn right, ..." with performing corresponding gestures in several levels. Entrained gestures (unconscious synchronized movement of hands or elbows to the robot's gesture, shown in Fig.3) appeared in many subjects.
3. The subject tries to go to the lobby.

The result can be summarized that:

1. The subjects' gestures are increased as the enhancing of robot's gesture. In other words, the subject's gestures are increased by entrainment and synchronization with the robot. Thus, the mutual gestures established the communicative relationship between the robot and the subjects.
2. Obtaining a joint viewing point by the robot's gestures, subjects understand the utterance of the robot.
3. The emerged mutual gestures help to understand robot's utterance.

Obtained Ideas about Body Properties of Robots

As the results of this and another cognitive experiments, we have obtained important ideas as follows:

1. Rich robot's behaviors induce various human communicative gestures that help utterance understanding.
2. Attention expression by the robot (such as pointing something with hands) guides the human's focus to the robot attention.
3. Robot's eye contact indicates that the robot intend to communicate with humans.
4. Sharing of a joint viewing point (a proper positional relation) establishes the situation where the human can easily understand robot's utterance.

2.3. The Software Architecture to incorporate the knowledge from cognitive science

We developed the software architecture for interaction-oriented robot. It is an extension of our previous research [9]. We incorporated the obtained ideas as '*Communicative unit*' into the previous architecture. The basic structure of the architecture is a network of '*Situated modules*'.

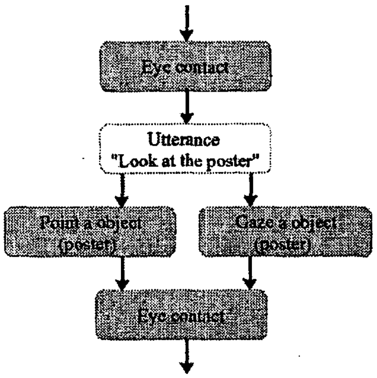

Fig. 5: Development of a Situated module

It has a merit in development of robot behaviors. Each *situated module* is implemented by coupling these *communicative units*.

Communicative unit

Communicative unit (communicative sensory-motor unit) is very basic unit that realizes a sensory-motor action for natural and effective human-robot communication. The experiments in cognitive science produced several essential ideas about the robot's body property. Each *communicative unit* is retrieved from the ideas. Concretely, we have implemented 'gaze object', 'eye contact', 'nod', and so forth as shown in Fig.4.

Although the implemented ideas are not so many to date, we can continuously develop such *communicative units* through the interdisciplinary approach. Then, we consider that the communicative ability of the robot will increase along with the development of the communicative units.

Situated Module

The basic structure of the architecture is a network of *situated modules*. For easy development of the modules, we define the *situated module* as:

A program that performs a particular robot behavior in a particular situation.

Because each module works in a particular situation, developer easily implements *situated modules* with concerning only the particular limited situation.

As shown in Fig.4, *situated module* is implemented by coupling *communicative sensory-motor units* with directly supplementing other sensory-motor units (particular utterance, positional movement and so forth). Fig. 5 expresses an example of implementing a *situated module*, which realizes pointing a poster. In the figure, brown boxes are *communicative unit*, and white box (utterance "Look at the poster") is directly implemented behavior.

Software architecture

Fig. 6 indicates all components of the software architecture. By executing *situated modules* sequentially, a robot autonomously behaves around environments and interacts with humans. The execution sequence of *situated* *modules* forms network as shown in Fig.7. The developer progressively develops *situated modules*, and adds them into the network in order to achieve the pre-determined robot tasks.

The architecture has the components for communication through computer networks. By connecting to *communication server*, some robots are able to execute behaviors synchronously. In addition, robots can give information to humans in natural communication as new information infrastructure. For example, when the robot and humans will talk about weather, the robot will obtain weather information from *the Internet*, and then it will speak "It will rain tomorrow."

Then, we briefly explain other components of the architecture. *Reactive modules* realize very simple and reactive behaviors such as avoidance. *Internal status* represents intention, a current task, and an emotional model. According to the *internal status, module control* plans the execution sequence of *situated modules*. Inputs from sensors are pre-processed at *sensor modules* such as speech recognition. *Actuator modules* perform low-level controls of actuators according to the order from *situated modules*.

2.4. Implementation of interactive behaviors

Based on the architecture, we have implemented interactive behaviors as *situated modules* into the developed robot. It was widely demonstrated (Fig.8-a), and then the robot 'Robovie' became popular with many children in Japan. Fig.7 shows the implemented 40 *situated modules* and their relationships. The robot autonomously exhibits friendly behaviors to play with humans, such as a handshake (Fig.8-b), hug (Fig.8-c), the game of `paper, stone and scissors' (a Japanese traditional game using hands, and used in a similar way to coin flipping) (Fig.8-d), and short conversations. It speaks more than 100 sentences and recognizes about 10 words in Japanese. It sometimes expresses idling behavior such as "scratch the head" and "fold its arms", which represent human-like behaviors. It sometimes performs daily work, which is currently patrolling around environments. It can also autonomously charge battery. We believe these functions "Play with humans", "Idling", "Daily work", and "Charge battery" are important for realizing natural robot behaviors.

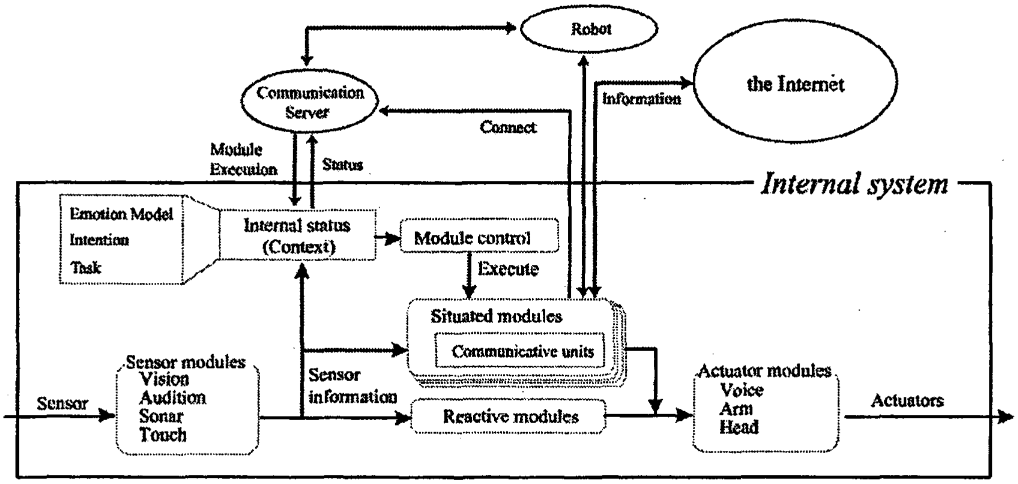

Fig. 6: Software architecture based on Situated modules and Communicative units

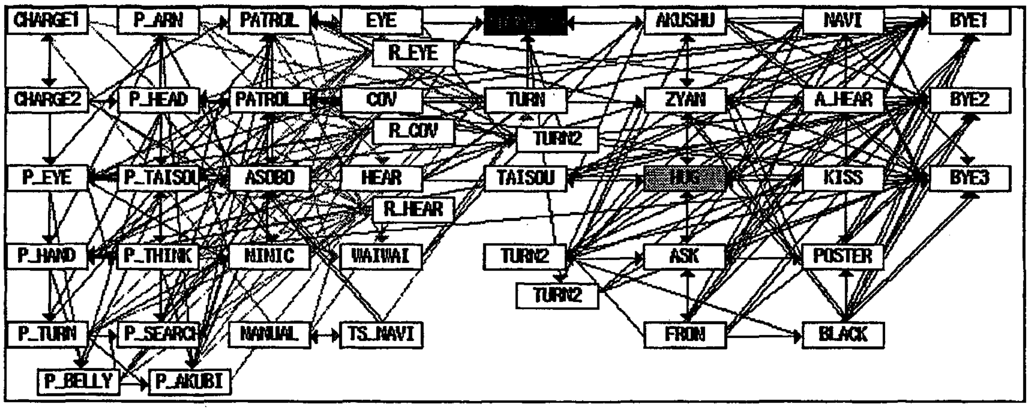

Fig. 7: Implemented situated modules and their relationships


(a) (b) (c) (d)

Fig.8: Autonomous interaction with humans

3. Evaluation

This section intends to verify that the robot has enough performance for interacting with humans. We performed an experiment to evaluate the robot and behaviors through comparing three behavior patterns: *Passive*, *Active*, and *Complex*. As the results, the experiment reveals how humans recognize the interactive humanoid robot.

3.1. Method

We evaluated the autonomous interaction through comparing three behavior patterns (Fig.9), that is:

Passive: The robot waits until a subject interacts. It says "Let's play, touch me". When the subject touches the robot, it exhibits one of the friendly behaviors. Then it waits again.

Active: The robot asks interaction to a subject. It says "Let's play, touch me". Once a subject touches the robot, it continues the friendly behaviors while the subject reacts to the behaviors.

Complex: In addition to the *Active pattern*, it sometimes exhibits *Idling* and *Daily work* (move around) behaviors instead of waiting.

We employed 31 university students as subjects. While five minutes, each subject observed one of the above behavior patterns. Then impressions of the robot were evaluated by using the SD method, similar to our previous research [10]. Subjects answered a questionnaire to rate in 28 adjective pairs (in Japanese) with 1-to-7 scales. In addition, subjects' behaviors toward the robot were analyzed as the unobtrusive measures.

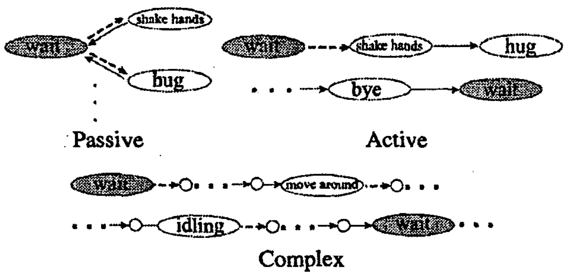

Fig.9: Examples of Compared 3 behavior patterns

3.2. Results

We report from the following six points of view about the results. As regards impressions, *Passive* pattern was highly evaluated. Meanwhile, other five viewpoints suggest that *Passive* pattern was rather not highly evaluated, where there is no statistical significant difference among behavior patterns.

Impressions of the robot

Factor analysis was performed on the SD method ratings for the 28 adjective pairs. By the Kaiser-Meyer-Olkin Measure of Sampling Adequacy, five

	Evaluation	Familiarity	Potency	Sociability	Activity	Communality
Good	**0.808**	0.252	0.127	0.003	0.146	0.755
Kind	**0.759**	0.110	-0.038	0.197	-0.209	0.671
Pretty	**0.690**	**0.514**	-0.111	0.132	-0.020	0.770
Exciting	**0.505**	0.442	0.153	0.182	0.355	0.633
Warm	0.451	0.074	0.110	0.399	0.117	0.394
Accessible	0.417	0.136	0.240	0.246	-0.085	0.318
Humanlike	0.336	0.116	0.167	0.312	0.137	0.271
Pleasant	0.186	**0.873**	0.112	0.166	-0.011	0.837
Friendly	0.313	**0.727**	0.059	0.175	0.001	0.660
Likable	**0.573**	**0.614**	-0.108	0.086	0.149	0.746
Cheerful	0.021	**0.527**	0.029	0.351	0.078	0.408
Favorable	0.453	**0.509**	0.130	0.302	0.002	0.573
Intelligent	0.331	0.448	0.252	-0.263	0.254	0.508
Showy	-0.033	0.079	**0.667**	0.263	0.279	0.599
Complex	0.012	0.021	**0.654**	-0.295	0.113	0.528
Sharp	0.112	-0.004	**0.640**	0.079	0.152	0.451
Full	0.226	0.339	**0.516**	0.203	0.213	0.519
Light	0.239	0.458	0.173	**0.657**	0.162	0.755
Agitated	0.195	0.202	-0.099	**0.556**	0.224	0.447
Frank	0.480	0.329	0.103	**0.528**	-0.129	0.645
Rapid	-0.024	0.022	0.374	0.040	**0.711**	0.648
Quick	-0.044	0.022	0.204	0.124	**0.574**	0.389
Interesting	0.377	0.351	0.084	0.163	0.390	0.452
Proportion	16.355	15.565	8.901	8.792	6.795	

Table 1: Factor Pattern of the SD ratings (Varimax normalized)

	Number of subjects in the condition	Distance to the robot [cm]	The time watching face [sec.]	Interpersonal behavior [Num. of subj. who did it]			Utterance [Num. of subj. who did it (total times)]	
				Give responses	Synchronize	Greet	Voluntary	Answering
Passive	10	44.0	187.1	1	1	0	2 (5)	5 (31)
Active	11	34.5	218.6	4	4	2	4 (12)	7 (53)
Complex	10	45.0	171.0	2	3	2	2 (19)	7 (77)

Table 3: Analysis of the subjects' behaviors

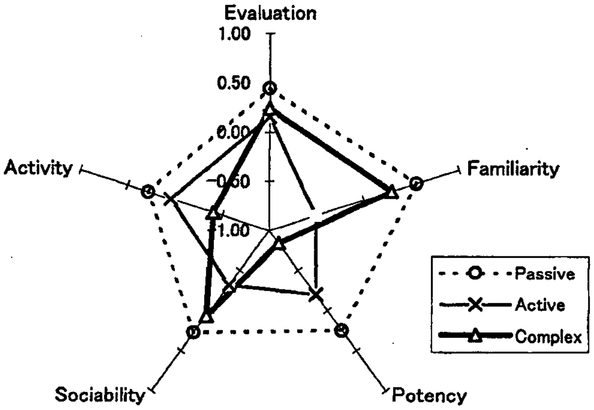

Fig.10: Illustration of the comparison of the impressions

	Num. of subjects	Evaluation	Familiarity	Potency	Sociability	Activity
Passive	10	0.45	**0.55**	**0.25**	0.28	0.28
Active	11	0.16	**-0.51**	-0.20	-0.32	0.04
Complex	10	0.24	0.29	**-0.84**	0.07	-0.41
p		0.82	0.06	0.04	0.40	0.33
			#1	#2		

Multiple Comparison #1:Passive>Active, #2:Passive>Complex

Table 2: Comparison of subjects' impressions
(factor scores of the SD ratings)

adjective pairs were omitted. According to the difference in eigenvalues, we adopted a solution that consists of five factors. Cumulative proportion of the final solution was 56.4%. The retrieved factor matrix was rotated by a Varimax method (shown in table 1). Along with the factor loadings, each factor was named *Evaluation, Familiarity, Potency, Sociability*, and *Activity* factor. Standardized factor scores were calculated to easily understand the results.

We have compared the factor scores of the three behavior patterns (Table 2, Fig.10). ANOVA (analysis of variance) detected a significant difference in *Potency* scores. Then an LSD (least significance difference) method proved that the scores of *Passive* are significantly bigger than *Complex* ($p<0.05$). Only as a suggestion, we applied an LSD method for *Familiarity* scores, in which there is an almost significant difference among three behavior patterns. As the result, the scores of *Passive* are significantly bigger than *Active* ($p<0.05$). That is, robots give best impressions when it behaves with the *Passive* patterns.

	Upper Arm	Fore-arm	Hand	Shoulder	Head	Body
Num. of Subjects	31	31	30	28	25	2
Avg. of touches	54.3	39.0	28.9	12.2	2.5	0.1
First touch [sec]	12	14	25	77	141	281

Table 4: Touched parts of the robot

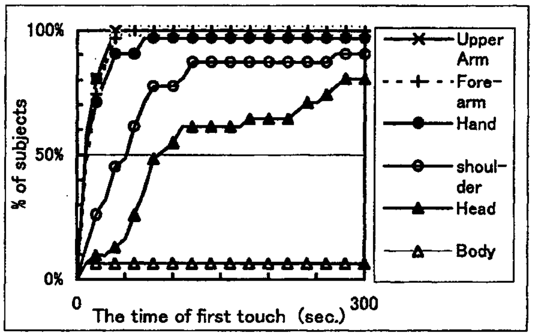

Fig. 11: The time of first touches

Spatial distance between the robot and subjects

At the beginning of the experiment, the robot said "touch me", and then almost all subjects approached the robot. Some of them stood almost one meter away from the robot and approached it only when it asked to touch; some stood very near of the robot where the moving arm of the robot nearly collided with him/her. We have measured the distance between the standing points of the subjects and the robot (Table 3: Distance to the robot).

Generally, humans keep the distance of 45 cm when they are talking familiarly [11]. In the experiment, the average of the distance was 41 cm. This is a shorter distance. We consider it is because the robot is not so tall and looks like a child in both the appearance and behaviors. In addition, the physical contact of the robot and subjects such as hugging and handshaking contributed to decrease the distance.

Touched parts of the robot

In the experiment, subjects touched the robot in response to the request of the robot. The robot detected the touches with skin sensors. We analyzed the record of the sensory input. Although there is no significant difference among three behavior patterns, we acquired meaningful findings about where the subjects touched. Table 4 indicates the result. 'Num. of subjects' means the number of the subjects who touched the parts of the robot, 'avg. of touches' means the average of how many times the subjects touched the parts, and 'First touch' means the average of the time when they touched the parts first time. About the 'first touch', we calculated the time of the subjects who did not touched the parts as 300 seconds (end time of the experiment).

Fig. 11 illustrates the relationship between the time since the experiment started and the number of the subjects who had touched the parts. Because the touches were the start signal of the interaction and the robot required it, almost all subjects touched the robot within ten several seconds from the start. About the communication among humans, psychologically, the parts to easily touch are arms, shoulders, heads, and bodies in that order. The result of the experiment is similar to this. Thus, we consider that subjects touched the humanoid robot as if they touched humans.

Eye contact

Eye contact is known as one of the important non-verbal communications, and our cognitive experiment has proved it too. With *communicative unit*, the robot controls its camera direction to the humans' face as the eye contact. As the result of questionnaires, seven subjects answered the eye motion was impressive. Most of the subjects watched the face (around the cameras) while the experiment (Table 3: The time watching face). The average of all subjects is 193.1 seconds. This is more than half of the five minutes experiments. Thus, the subjects focused their attention on the face of the robot.

Subjects' behaviors toward the robot

Some of subjects gave responses to the robot's utterance; some greeted the robot when it greeted the subject; some moved his/her body synchronously to the robot's body movement such as pointing a poster on a wall. We consider that these subjects' behaviors were performed with little intention to convey information to the robot. Rather, these behaviors were similar to what we unconsciously perform in daily communications among humans. Thus, each of these subjects' behaviors is a kind of interpersonal behaviors (Table 3: Interpersonal behaviors). Fig. 12 shows the number of the subjects who performed such the interpersonal behaviors and how many kinds of the interpersonal behaviors they did. In *Active* condition, six subjects performed the interpersonal behaviors and three of them performed more than one kind. On the other hand, in *Passive* condition, two subjects performed one kind of the interpersonal behaviors. We believe that the subjects who performed these behaviors regarded the robot as the target of communication.

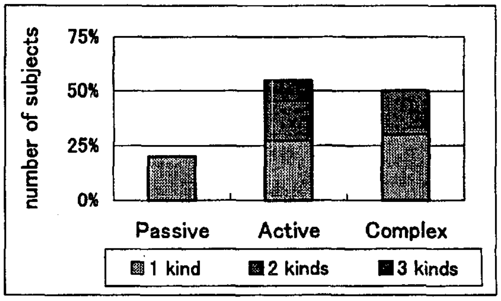

Fig. 12: Emergence of Interpersonal behaviors

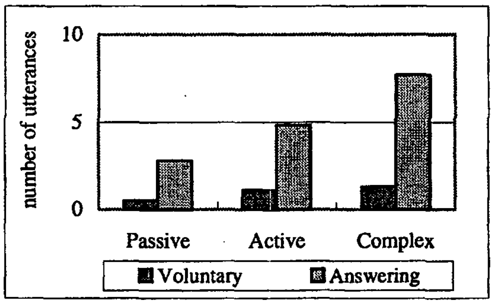

Fig. 13: Subjects' utterance to the robot

R: Robovie, S: Subject
R: Please talk to me.
S: Let's shake hands
R: Let's shake hands
(It responded correctly, and they shook hands)
Where are you from?
S: I'm from Nara. And you?
R: I'm from ATR.
(Although it did not recognize the utterance, it seems to correctly respond as designed.)

Table 5: Example of conversations between a subject and the robot

Subjects' utterance

Subjects' utterance proved that many subjects regarded the robot as the target of communication as well. The robot can speak more than 100 sentences, and it asks something like "where are you from?" and "please talk to me". More than half of the subjects answered the robot's asking (Table 3: answering utterance), such as "I'm from Kyoto". Some of the subjects voluntarily talked to the robot (Table 3: voluntary utterance), such as "Let's shake hands". The averages of the number of answering and voluntary utterance are shown in Fig. 13. Table 5 indicates an example of typical conversation between subjects and the robot. The robot continually exhibited the friendly behaviors and asked something, and then subjects answered it and asked something to the robot.

3.3. Discussions

The results of the experiment indicated that subjects interacted with the robot in the similar manner to how they communicate with humans. That is:

- Friendly spatial distance
- Similar parts to be easily touched
- Communication with eye contact
- Interpersonal behaviors
- Answering / voluntary utterance

Thus, they naturally interacted with the humanoid robot. We believe many subjects were absorbed in the interaction and they regarded the robot as the target of the natural communication. In other words, the interactive behaviors of the robot established *communicative relationships* between humans and the robot.

These *communicative relationships* between humans and robots have important roles in human-robot communication. Sperber proposed the *relevance theory* [12], where humans communicate among themselves by inferring the minds of others. This is different communication model against the 'code model', where a sender gives information (signals) to a receiver using a presupposed common code for encoding and decoding. Based on the *relevance theory*, Ono and his colleagues proved the importance of the *communicative relationships* between humans and a robot [13], that is humans easily understand the utterance of the robot if they build *communicative relationships* with the robot.

The results of the experiment indicate that the *communicative relationships* are established by enough physical expression ability, the software architecture to incorporate cognitive knowledge, and the implemented interactive behaviors. For the interaction-oriented robots that we are trying to realize, it is indispensable to establish these communicative relationships with humans.

4. Conclusion

We have reported the development of a new interaction-oriented robot and interdisciplinary approach between cognitive science and robotics. The robot has enough physical expression ability and autonomously interacts with humans. The cognitive ideas about the practical use of the body property are incorporated into the software architecture. Through the experiment, we verified the robot's performance for interacting with humans by the behaviors of the subjects toward the robot.

In the experiments, many humans interacted with the robot in the similar manner to how they communicate with humans. They performed interpersonal behaviors such as giving responses to the robot and voluntarily spoke to it. Thus, they regarded the robot as the target of the natural communication. That is, the communicative relationships between humans and robots are established by the interactive behaviors of the robot. We think this ability of establishing communicative relationship is necessary for interaction-oriented robots.

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