# Multi-robot Cooperation for Human-Robot Communication

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**Abstract**

*This paper illustrates how robots can effectively cooperate to facilitate communication with people. We expect that communication robots will play an important role in our daily life. Although these robots can communicate with each other by radio, infrared, or other invisible means, our results show that it is important to human understanding that they are able to communicate with each other by voice and gestures as well. This lets humans know that the robots can talk with them and among themselves. Thus, humans come to regard the robots as appropriate targets for natural communication.*

## 1. Introduction

Recent advances in robotics technology enable robots to provide people with a more natural interface for communication Regarding robots employed in public places, Schulte and his colleagues developed museum guide robots [1], while Asoh and his colleagues developed office robots that obtain knowledge through interaction with humans [2]. In Japan, Matsushita and NEC have started to develop robots that participate in our daily life. Waseda University [3], Honda [4], and Sony have built biped robots that appear human-like. Kobayashi and his colleagues' research centers on robots that have a human-like face [5]. We believe that these kinds of robots will exist as our partners in daily life and will keep us informed through their communicative functions. Thus, these communication robots will become a new form of information media.

Traditional research on human-robot interaction focused mainly on communication between people and one robot and on the robot's internal workings. We consider it important for these robots to interact with other robots as well [6]. We selected pointing behavior as the means by which the robot expresses its ability to interact in part because the emergence of this triad marks an important step in child development.

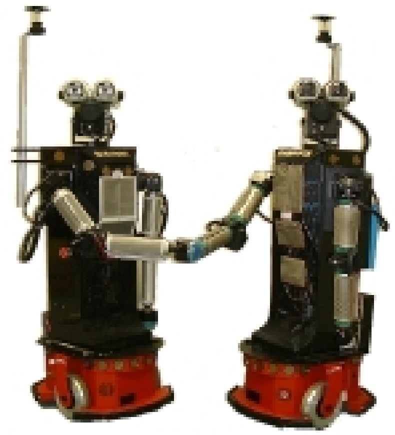


**Figure 1.** Robovie's body gives it the ability to express itself well enough for interpersonal communication

In this paper, we propose an effective cooperation method for multi-robots in the interests of promoting human-robot communication. In the future, there will be many communication robots in our daily lives, and the robots will be able to communicate with each other by invisible means, such as radio and infrared. We also consider it important for those robots to express communication by voice and gestures, even if they really communicate invisibly. It lets humans know those robots can communicate with each other and interact with their surrounding environments.

## 2. Implementation

### 2.1. Interactive humanoid robot "Robovie"

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

Size is important for an interactive robot. So as not to threaten humans, we set the size to 120 cm, which is the same as that of a typical junior high 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 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 to human voices, and 24 ultra-sonic sensors for detecting obstacles. Each eye has a 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 sensitive skin sensors using pressure-sensitive conductive rubber. With the actuators and sensors working together, the robot can generate enough behaviors to entrain humans into communication with humans. 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.

Robovie is a self-contained autonomous robot. It has a Pentium III PC on board for processing sensory data and generating behavior. 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. Software architecture

We developed a software architecture for interaction-oriented robots [7]. The basic structure of the architecture is a network of 'situated modules' [8]. It has merit in development and communication with humans. The developer can progressively add *Situated modules* to easily develop the robot system. Moreover, cognitive science experiments are used to devise the basic components of the modules, which are named `communicative units.' Each situated module is implemented by combining these communicative units.

***Communicative unit***

A communicative unit (communicative sensory-motor unit) is a very basic unit that realizes a sensory-motor action for natural and effective human-robot communication. The results of the cognitive science experiments produced essential information about the robot's embodiment. Each communicative unit is based on these results. Consequently, we have implemented 'gaze at object', 'eye contact', 'nod', and so forth.

Although we have not implemented many ideas to date, we can continually develop such communicative units through an interdisciplinary approach. We believe 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, the developer can easily implement situated modules with concern only for a particular situation.

A situated module is implemented by coupling communicative sensory-motor units with other directly supplementing sensory-motor units (particular utterance, positional movement and so forth).

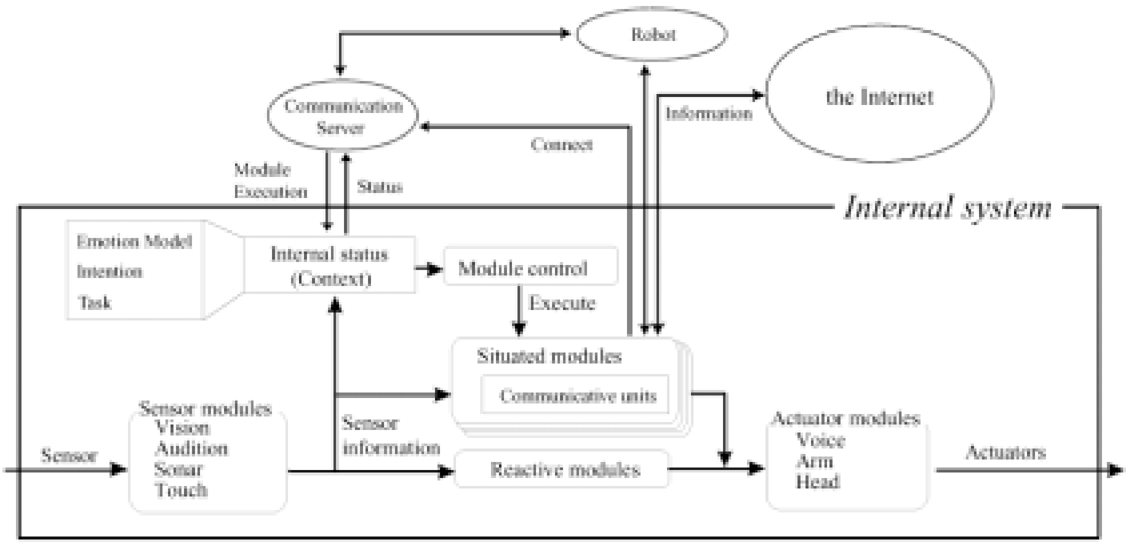



Figure 2. Software architecture based on Situated modules and Communicative units

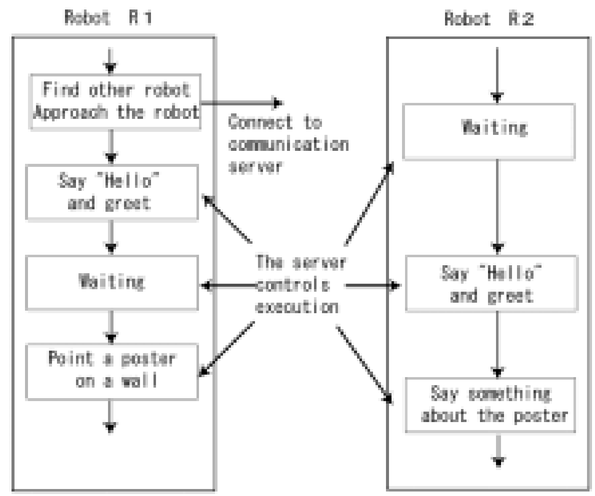



**Figure 3.** Modules for robot-robot communication

***Software architecture***

Figure 2 indicates all components of the software architecture. By executing situated modules sequentially, a robot autonomously acts in different environments and interacts with humans. The developer progressively devises situated modules, and inserts them into the network so that the robot can achieve the pre-determined task.

By connecting to a communication server, some robots are able to act in synchrony. In addition, robots can give information to humans in natural language. This is a new kind of information infrastructure. For example, when the robot and humans talk about weather, the robot will obtain weather information from the Internet, and then it may speak “It will rain tomorrow.”

Next, 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. The module control plans the execution sequence of situated modules according to the internal status. Inputs from sensors are pre-processed at sensor modules, such as speech recognition. Actuator modules perform low-level controls of actuators according to the orders from situated modules.

### 2.3. Communication with other robots

We developed a robot system using two humanoid robots to communicate with each other according to the following sequence:

1. Find and approach a colleague robot.
2. Start to send/receive data.
3. At the same time, two robots express communicative behaviors with voice and gestures.

An example of how the sequences are implemented is shown in Figure 3. Arrows in the figure represent the execution order of the modules and data flow. Using these modules, R1 points at a poster on a wall and R2 says something about it. To an observer, it looks like they are talking about something located in their surrounding environments. Consequently, observers think the robots can interact with others and surrounding environments. Thus, we can easily develop robots that interact with other robots and environments.

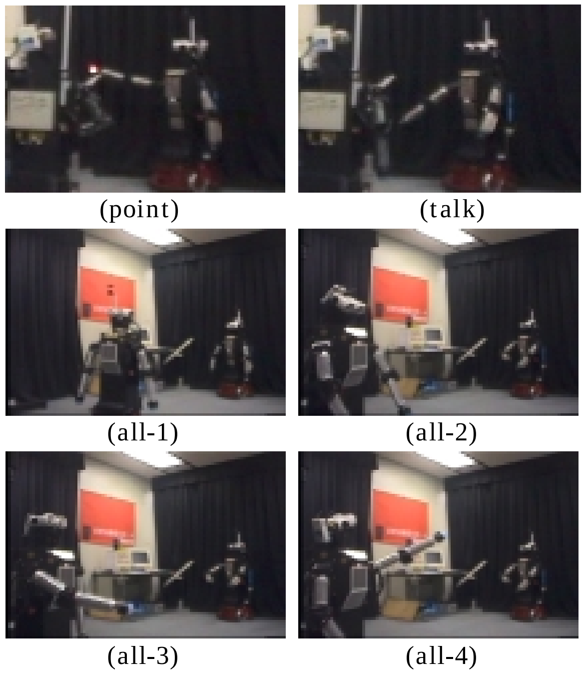



**Figure 4.** Scenes of the experiment

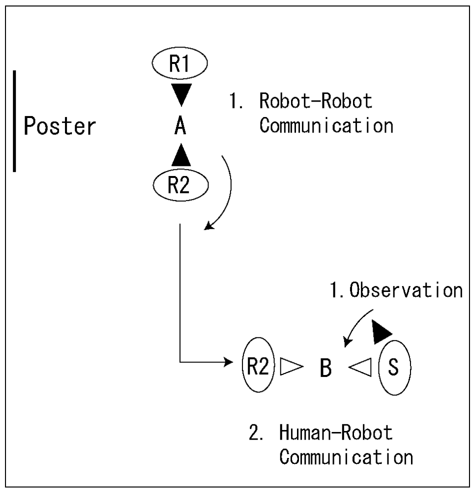



**Figure 5.** Outline of the experiment

### 2.4. Interaction with environments

In the field of developmental psychology research, pointing behavior is known as a form of a triad expression. Human infants cannot build relationships between more than two things at early stage of their development. That is, they only form dyads: “human to human” or “human to object.” After further development, however, they can share their attention with others by such pointing behavior. This

| | Num. of subj. | Under-standing | Give responses | | | |
|---|---|---|---|---|---|---|
| | | | Nod | Look doubtful | Pointing | Gaze |
| Point | 12 | 12 | 2 | 3 | 0 | 11 |
| Talk | 12 | 6 | 2 | 5 | 1 | 6 |
| None | 12 | 6 | 1 | 1 | 0 | 5 |

**Table 1.** Subjects' understandings and behaviors

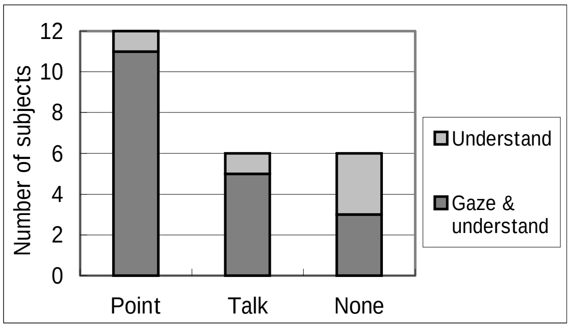



**Figure 6.** Subjects' understandings

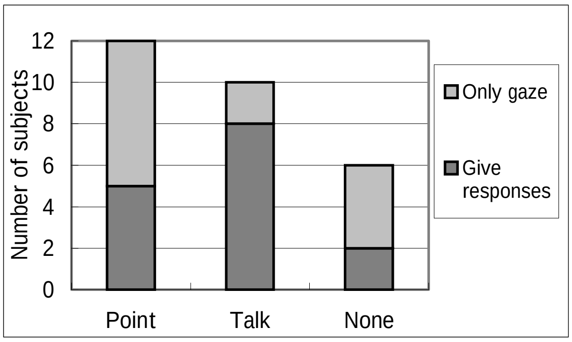


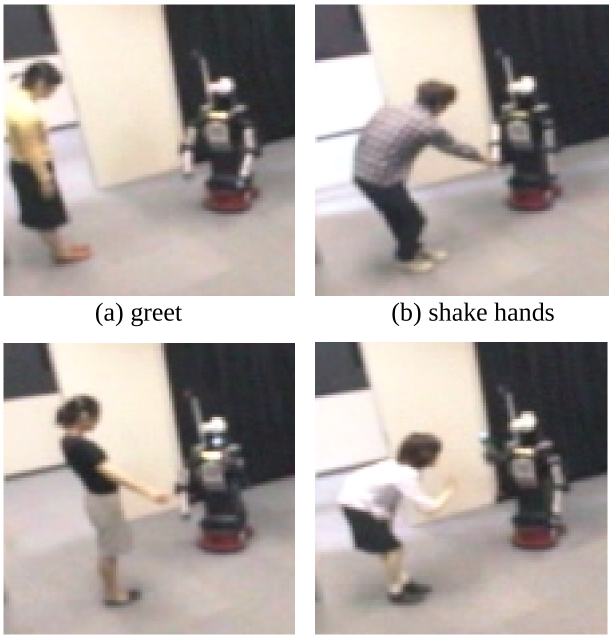

**Figure 7.** Gave responses

joint attention mechanism forms the triad: "human to object to human."

Because we have also studied the joint attention mechanism in conjunction with pointing [9], we implemented pointing behavior using the results of that study. For example, we used eye-contact behavior to express communicative intention, and drawing the human's attention by looking and pointing at an object. These eye motions are verified as being useful.

## 3. Experiments

We analyzed how communication expressions between robots and interaction with the surrounding environment affects human observer. That is, how the observation of robot-robot communication, including the expression of robot-robot communication and the expression of triads, influences human-robot communication. By executing *situated modules* in synchrony, two robots seem to interact and communicate by voice and gesture. In addition, the



(a) greet (b) shake hands
(c) pointing (d) bye-bye

**Figure 8.** Subject's behaviors

robot points at an object in its environment, such as a poster on a wall, then it talks about the object. Thus, observers think the robot can interact with others and the environment.

### 3.1. Evaluation method

We performed the experiment to verify the effect of our developed multi-robot system, which expresses robot-robot communication and interaction ability with surrounding environments.

We used 36 subjects (18 men, 18 women). Each subject observed robot-robot communication, and then one of the robots talked to the subject. There were three patterns of robot-robot communication. Comparison of the three patterns indicates the effects of the robot-robot interaction on the communication between subjects and the robot.

Figure 5 shows the outline of the experiment. The room is 4.5 m square. *R1* and *R2* indicate Robovies, *S* indicates a subject. The sequence of the experiment is given below:

1. A subject was instructed to observe the robots, and to respond to them if they came close to him/her.
2. At *A*, two robots communicated according to the following conditions.
3. Robovie *R2* came close to the subject at *B*.
4. *R2* communicated with the subject.

There were three conditions of robot-robot communication.

**Point:** *R1* and *R2* talk while pointing at the poster (Fig.5 poster, Fig.4 point) and the subject. Then, *R2* approached the subject.

**Talk:** *R1* and *R2* talk while performing body movements as complex as *Point* (Fig.4 talk). However, they did not point at anything.

**None:** The two robots do not talk at all. Immediately *R2* approached the subject.

After the robot-robot communication (Fig.4 all-1), *R2* greeted the subjects at *B* (Fig.4 all-2), asked to shake hands (Fig.4 all-3), and then pointed at *R1* and saying, "It is interesting" (Fig.4 all-4). Finally, it says, "Bye bye."

### 3.2. Results

Table 1 shows the results of the experiment. *Nod, look doubtful*, and *pointing* means subjects gave these responses to the robot's utterance. *Gaze* means subjects gazed at *R1* when *R2* pointed at *R1*.

These results prove the following two effects on human-robot communication. That is, observation of robot-robot communication and interaction with their environment causes humans to communicate naturally with robots, and understand the utterances of the robots.

**Effects on understanding of robot's utterances**

After the experiment, we asked subjects, "What did *R2* indicate by pointing?" (R2 pointed R1 after it came close to humans.) All subjects observing the *Point* condition understood that *R2* pointed at *R1*. On the other hand, half of subjects observing the *Talk* and *None* conditions did not understand it. The number of subjects who understood it and gazed in the pointing direction (it was they would understand it immediately) is illustrated in Figure 6.

A chi-squared test proved the significant differences on the number of the subjects who understood the pointing utterance ($\chi^2_{(2)} = 9.00, p < 0.5$), and the subjects who understood it with gazing in the pointing direction ($\chi^2_{(2)} = 11.59, p < 0.01$). As the result of analysis of residuals, the number of subjects in the *Point* condition who understood it is significantly larger (residual r = 2.99, p<0.01). Thus, it is proved that visible and audible communication between robots and interaction with their environment improves subjects' understanding of the robot's utterances.

**Effects on promoting human-like natural communication**

Many subjects responded to the robot's utterance as if the robots were human (Figure 8). We analyzed the relationship between experimental conditions and the responses (Figure 7). Here, 'give response' means the subject performed *nod*, *look doubtful*, or *pointing*. We think some subjects *gazed* in the pointing direction instead of giving responses.

A chi-squared test proved the significant differences on the number of the subjects who gave responses or gazed toward the pointing direction ($\chi^2_{(2)} = 9.00, p < 0.5$). Results of the analysis of residuals indicate the number of the subjects in the *Point* condition who performed these responses is significantly greater than in the other conditions (residual r=2.27, p<0.5). It also proved that the number of the subjects in *the None* condition who did not perform these responses is significantly greater than that of the other conditions (residual r=2.83, p<0.01).

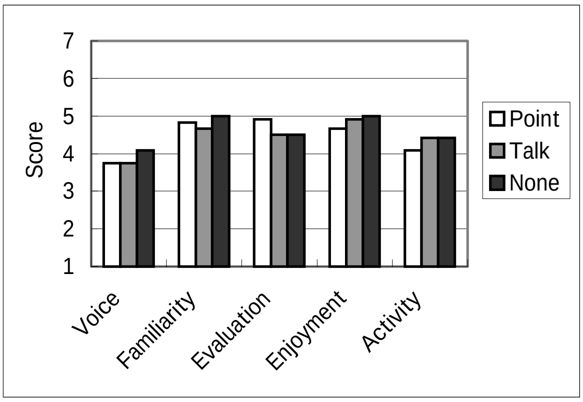



**Figure 9.** comparison of subjective voice quality and impressions of the robot

## 4. Discussion

The results indicated the effects of the system that expresses robot-robot communication. Moreover, we were able to verify the validity of the results from two aspects.

First, we tested the theory that the subjects got accustomed to hearing the robot's voice (Figure 9). That is, the subjects in *Point* and *Talk* conditions could get more accustomed to listening to the robot's synthesized voice than the subjects in the *None* condition. After the experiment, we asked the subjects about the easiness of hearing the robot's utterance. The ANOVA (analysis of variance) result told us there is no significant difference ($F_{(2,3)} = 0.25$). It supports our conclusion that the observation of robot-robot communication and their interaction with the environment aids understanding of a robot's utterances more than simply listening to the robots' voice.

We expected about negative effects of robot-robot communication. For example, some subjects might think, "the robot that talks with another robot is strange, fearful, and so forth." However, it seems that there were no such negative effects. We also investigated the impression the robot leaves on people [10] to check for negative effects (Figure 9). We found that there were no significant differences ($F_{(2,33)} = 0.21, 0.51, 0.19, 0.28$ for familiarity, evaluation, enjoyment, and activity, respectively).

In previous research [11], we have discussed about the communicational relationships between a human and a robot. That is, once they build the relationships, humans can understand the utterances of the robot. From the viewpoint of communicational relationships, a human can joins the network of relationships among robots and environments, naturally and smoothly communicating with each other.

## 5. Conclusion

We proposed a human-robot communication system based on the observation of robot-robot communication. Robots express their invisible communication by visible means, such as voice and gestures. The expression of the communication lets humans know those robots can communicate with each other and interact with surrounding environments. In the experiment, we verified our approach by using a robot that has the ability to express itself physically. Humans observed the communication between multi-robot and the interaction with their environment, learning to easily understand the robot's utterances. Moreover, the observation makes human-robot communication as natural and smooth as human-human communication.

## Acknowledgement

This research was supported in part by the Telecommunications Advancement Organization of Japan.

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