Emotional Communication Robot: WAMOEBA-2R - Emotion Model and Evaluation Experiments -

Tetsuya Ogata and Shigeki Sugano

Department of Mechanical Engineering, Waseda University
3-4-1 Okubo Shinjuku Tokyo 169-8555, Japan
{ogata, sugano}@paradise.mech.waseda.ac.jp

Abstract. This study aims to clarify the cooperation intelligence of robots. This paper describes the autonomous robot named WAMOEBA-2R that can communicate with humans by both an informational and a physical way. WAMOEBA-2R has two arms of which each joint has a torque sensor to realize the physical interaction with humans. Also it has the function of the voice recognition and the face recognition. The arms are controlled by a distributed agent network system. The network architecture is acquired in a neural network by the feedback-error-learning algorithm. We surveyed 150 visitors at the '99 International Robot Exhibition held in Tokyo (Oct. 1999) to evaluate their psychological impressions of WAMOEBA-2R. As the result, some factors of the human-robot emotional communication were discovered.

1 Introduction

In recent years, interactive simulation games or pet robots have become popular (as represented by “Furby,” “AIBO,” Omuron pet robot, etc.). [1][2] Most of conventional robots are designed the behavior patterns sometimes involving the growth process and/or the learning process by the designer based on findings of psychology. The impression of these robotic toys on humans is similar to that of other living things, such as dogs and cats. Usually, the design of these robots focuses only on the user's satisfaction. The morphologies of pet robots, usually imitating living things, are highly influenced by the psychological side of human beings such as children. It is difficult to design these robots from this point of view. Based on this background, this present study aims to clarify the characteristics and the design method of “emotional interaction” which has the effectiveness to realize cooperation which can be achieved between humans and robots.

This research adopts the methodology of constructing communication models of robots by referring to the autonomy of living creatures. We thought that the autonomy of a living creature is the “adjustment” to the environment caused by the instinct of “self-preservation.” Presently, we have developed the autonomous robot, WAMOEBA-2 (Waseda Amoeba, Waseda Artificial Mind On Emotion BAse) to demonstrate the possibility of human cooperation. By proposing the “emotion model” of robots, which refers specifically to the endocrine system which has the particular function of “homeostasis” which helps to generate the body conditions recognized as feelings, such as tension in the muscles, shrinking of the pupils, and a rise in temperature, etc., to keep the internal conditions of the living organisms using hormones, we have achieved this. [3]

This paper describes the arm-hand system and the audiovisual system to enhance the behaviors and the communication functions of WAMOEBA-2. Further, the functions of the autonomous robot WAMOEBA-2R (Refine), which has had these systems installed described and the factors concerning the emotional communication of robots are described by the results of the questionnaire distributed at the ‘99 International Robot Exhibition held at Tokyo Big Site, Japan, Oct., 1999.

2. Emotional Communication and Design Concepts

Most of the conventional feeling models are constructed using a static rule such as finite-state-automatons. However, no common theory has been formulated on the classification of feelings, because all theories depend on individual human experiences.

Pfeifer noted that the simple behavior of robots could be interpreted as “feelings” by observers [4] referring to the “Fungus Eater” proposed by Toda [5]. He insisted that feelings are not generated from the explicit structure designed by the human beings but emerged from the sympathy of the observer.

In an “emotional communication,” a human's empathy towards the machinery is important, and we think that the three factors which cause the empathy are as follows.

- (i) The robot does not need the standardization of the environment.
- (ii) The interface of the robot is not limited.
- (iii) The communication scenario is not set to the robot.

These are factors which make users not aware of the designer of the machine. In conventional pet robots, these three elements are concealed as much as possible. However, it is extremely difficult to keep these elements completely hidden from the user. There are many cases in which the user becomes tired of the notification of the communication scenario designed a priori.

We thought that it was possible to satisfy the three conditions of the robots by referring to the autonomy of living creatures and have developed an autonomous robot, WAMOEBA-2, to carry out the experiments concerning the emotional interaction between human beings and robots. For the condition (i), WAMOEBA-2 was designed as a behavior based [6] robot on which control computers and batteries are installed. For the condition (ii), WAMOEBA-2 has the audiovisual sensor to be able to detect the human's information. The morphology refers to living creatures for humans to be able to imagine the style of communication easily. For the condition (iii), WAMOEBA-2 communicates with human beings by the original emotion model which refers to the human endocrine system described in Chapter 5.1 in detail.

3. Hardware and System Architecture of WAMOEBA-2R

3. 1 Arm system

The collected comments of the questionnaire at the '97 International Robot Exhibition [7] highlighted the importance and the problems of the arm system on WAMOEBA-2, more specifically, many people who were interested in the motions of the arms, and tried to shake hands with the arm. The arm system on WAMOEBA-2 was a simple mechanism that allows two degrees of freedom with the link mechanism. The main objective of the arm system is to facilitate gesturing. The motion of the arm was slight, so there were some comments such as "I can not understand the intention of the arm motions." and "The arm seems to be broken when I touch it." within the questionnaire.

It is thought that the arm system is an important hardware from the viewpoint of robot intelligence. Based on the comments, we developed a new WAMOEBA-2 arm system. T. Morita proposed the basic theory of the arm system for robots that can co-work with human beings. [8] We referred to this basic theory when designing the new WAMOEBA-2 arm system. Fig. 1 is a configuration diagram of the arm system developed by this research. The two requirements for this arm are as follows:

1) It must be installed on an independent robot for ease tasks.
2) It must safely enable physical interactions with human beings.

From the aspect of 1), the arm must be compact and light, and consume less electric power. The total reach of this arm is 450 [mm], the weight is 3.8 [kg], and the electric consumption is 50.5 [W]. All control devices, such as DC-DC converters and the driver circuits, can be installed on WAMOEBA-2. The arm has four degrees of freedom, and the maximum payload is 2.5 [kg] in the critical posture.

From the aspect of 2), the force control of each joint, but not by the end effector, is indispensable for safety in the physical interaction between the robot arm and human beings. A strain gage is installed directly on each joint axis to detect the torque of each joint. The end-effector speed was set at 0.6 [m/s] maximum so that the human beings are not afraid of the motions of the arm.

Moreover, we developed the 1 D.O.F. gripper hand which has a ball screw and a slider mechanism.

From the aspect of 1), the size is the same level of human's palm. The weight of the hand is 500 [g] and the electric power consumption is 2.5 [W]. The speed of the slider is 20 [mm/s] and the maximum grasping power is 6 [kg]. Furthermore the hand can detect the holding object by the photoelectric sensor and can sense the grasping power by the FSR sensor.

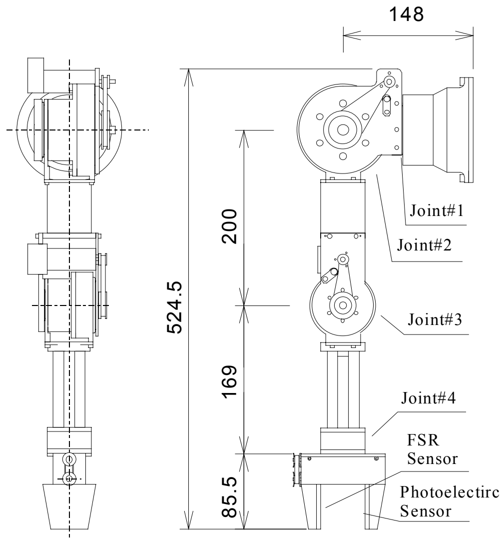

Fig. 1. Assembly draw of WAMOEBA-2R Arm-Hand Mechanism

Fig. 2. Photograph of WAMOEBA-2R

3.2 Computer System

WAMOEBA-2R (Refine) was composed of installing the arm-hand system into WAMOEBA-2. The photographs are shown in Fig. 2. Table 1 shows the specification of WAMOEBA-2R.

The control system consists of two computers (Pentium III 500 CPU). One computer employs the joint servo control and the joint torque control, and the other computer controls the sensor system. The control algorithm is implemented by software using gcc on RT-Linux. The PWM pulses generated in the I/O interface board control each motor driver. An A/D converter board detects the torque data on each joint.

Table 1 Specification of WAMOEBA-2R

Dimensions		1390(H) x 990(L) x 770(W) mm
Weight		Approx. 130 kg
Operating Time		Approx. 50 min
Max speed		3.5 km/h
Payload		2 kgf/hand
External DOF	Neck	2
	Vehicle	2
	Arm	4 x 2 = 8
	Hand	1 x 2 = 2
Internal DOF	Cooling Fan	10
	Power Switches	4
External Sensors	Image Input	CCD Cameras x 2
	Audio Input	Microphones x 3
	Audio Output	Speaker
	Distance Detection	Ultrasonic Sensors x 4
	Joint Torque	Torque Sensers x 6
	Grip Detection	Photoelectric Sensors x 2 Pressure Sensors x 2
	Object Detection	Touch Sensors x 8
Internal Sensors	Temperature	Thermometric Sensors x 8
	Battery Voltage	Voltage Sensor
	Motor Current	Current Sensor
Material		Duralumin, Aluminum
CPU		Pentium III (500MHz) x 2
OS		RT-Linux

3. 3 Audiovisual system

WAMOEBA-2R processes the camera images using an IP5000 board (Hitachi co.). Concretely, WAMOEBA-2R can detect the moving area, generate the distance map, and learn the deferent human faces (Max. 9 humans) by back propagation neural network. The face recognition function detects nose, eyes, mouth, and entire face areas using the template matching shown in Fig. 3. The recognition rate is approx. 70 [%].

Moreover, WAMOEBA-2R speaks some registered Japanese words and can recognize unspecified speaker's speech.

Fig. 3. Face Image Template and Recognition Result

4. Behavior Algorithm of WAMOEBA-2R

4.1 Model of endocrine system

The original characteristic of WAMOEBA-2R is the internal mechanism architecture for modeling the endocrine system of humans. The endocrine system has the particular function of "homeostasis" which helps to generate the body conditions recognized as feelings, such as tension in the muscles, shrinking of pupils, and a rise in temperature, etc., to keep the internal conditions of the living organisms using hormones. It is thought that, for robot hardware, these systems correspond to the control mechanisms of electric power consumption and circuit temperature, etc., for which WAMOEBA-2R receives the battery voltage and the driving current. Moreover, using ten temperature sensor ICs, it can acquire the temperature of eight positions in WAMOEBA-2R, which are the motors (of the head, the neck, the shoulder, the elbow, and the motor chair) and the circuits (of the image-processing board and A/D boards, etc.) It can control the output of the cooling fans, and switch the power supply of each motor on or off by itself.

WAMOEBA-2R controls these internal mechanisms using the hormone parameters calculated by the original algorithm "Self-Preservation Evaluation Function." This function is a kind of fuzzy set membership function which converts sensor input into the evaluation values of durability (breakdown rate) of robot hardware between 0-1. Each function consists of two sigmoid functions in order to simulate the properties of human senses, and it has one minimum value which stands for the best state for the self-preservation of the robot. This is defined as follows.

$$E(s_i) = \sigma_l(s_i) + \sigma_h(s_i) \tag{1}$$

$$\sigma_l(x) = \frac{1}{1+\exp|\frac{x-\theta_l}{\mu_l}|}, \quad \sigma_h(x) = \frac{1}{1+\exp|\frac{\theta_h - x}{\mu_h}|}$$

When this value is close to zero, the state of self-preservation is positive, and if this value gets close to one, the state is negative. WAMOEBA-2R has seven kinds of self-preservation evaluation functions that correspond to eleven internal and external sensors. The shapes of these functions are chosen depending on the basic hardware specs. For example, the evaluation function of the voltage of battery is shown in Fig. 4. In this case, the shape of the function is decided depending on the lowest voltage of the circuit drive and the standard voltage of the battery.

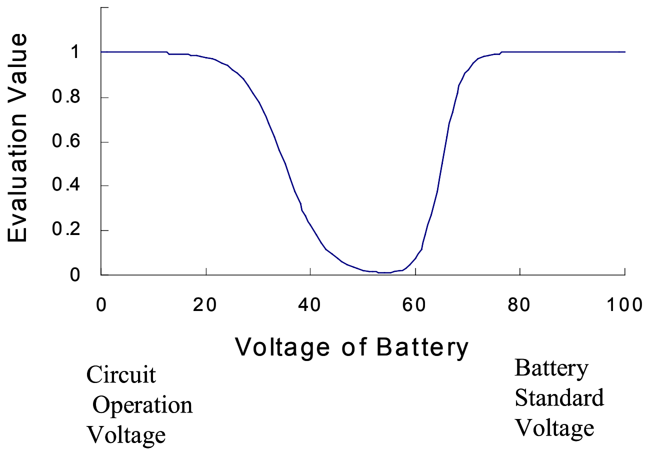

Fig.4 Evaluation Function of Voltage Battery

There are various kinds of the evaluation function of self-preservation E_i according to each sensor. Therefore, about the vector x = $(E_1, E_2, \ldots, E_i, \ldots, E_n)^T$, the following value can be calculated by each step cycle.

$$P = |\mathbf{x}| = \sqrt{\quad E_i^2} \tag{2}$$

This is the absolute value expressing the good/bad evaluation of self-preservation of robots. In the behavior-adjustment system, 4 adjustment hormone parameters are calculated by using the P value corresponding to 4 conditions, i.e. weather the evaluation value is good or bad (mood), and weather the value changes dynamically or not (arousal). WAMOEBA-2R calculates the output of the hormone parameters H_i {i: 1-4} using the total value P of all self-preservation evaluation functions in every program cycle as follows.

$$\frac{dH_i}{dt} = \alpha_i \cdot \left(P - P^{th}\right) + \beta \cdot \sigma_i | \frac{dP}{dt} | + \gamma \cdot \left(H_i - H^{th}\right) \tag{3}$$

where, α, β and γ are coefficients that correspond to the potential, the change quantity, and the stabilization. α is a 0/1 coefficient which indicates if the hormone output is continuous. P^{th} and H^{th} represent the standard values regarding P and H. $\sigma_i(x)$ is the sigmoid function which suppresses dP/dt within the range of 0-1. There are four kinds of hormone parameters [H_1 to H_4] corresponding to four conditions: if the evaluation value P is positive or negative (mood), and if P changes dynamically or not (arousal). These hormone parameters affect many hardware conditions such as the sensor gains, motor speed, temperatures of the circuits and energy consumption in parallel. The affects of each hormone are decided by referring to the physiology [9] shown in Table 2. Table 3 shows examples of the correspondences between the morphologies of emotional expressions caused by the hormone parameters. However, these are not fixed but are changed by the mixture condition of the four hormone parameters.

Table 2. Affects of the Hormone Parameters of WAMOEBA-2R

		H1	H2	H3	H4
Actuator Speed		Up	Down	Down	Up
Cooling Fan Output		Down	Up	Up	Down
Camera Viewing Area		Down	Up	Up	Down
Sensor Range		Down	Up	Up	Down
Sound	Volume	Up	Down	Down	Up
	Speed	Up	-	Down	Up
	Pitch	Down	Down	Up	Up
LCD Color		Red	Blue	Yellow	
Emotion		Anger	Sadness	Pleasure	Expect

Table 3. Expressions of WAMOEBA-2R by Hormone Parameters

Radical Unpleasantness	cause	Bumper switches, Ultra-sonic range sensors (radical approach)
	expression condition	Decrease of the viewing angle, Increase of the motor speed, Red color expression on the LCD and Low voice
Unpleasantness	cause	Temperature of the motors and the electrical circuits, Ultra-sonic range sensors
	expression condition	Increase of the viewing angle, Decrease of the motor speed, Blue color expression on the LCD
Pleasantness	cause	charge
	expression condition	Decrease of the viewing angle, Decrease of the motor speed, Yellow color expression on the LCD

The influence level e_k of each body condition k, (motor speed, viewing angle etc.) are calculated by following equation.

$$e_k = \sum_{i=0}^{4} m_i H_i \qquad (4)$$

$$\text{where,} \quad \sum_{i=0}^{4} m_i = 0$$

e_k is added to the standard output value of the condition k.

4.2 Motion Control Algorithm1

We proposed the "motor agent [9]" as a behavior generation mechanism of WAMOEBA-2 referring to other research. [10][11] In the motor agent algorithm, each motor collects all sensor information and other motor driving conditions through the network in the robot's hardware. Each motor determines its actions autonomously according to this collected data. The motion command a_i of the motor i is calculated as follows:

$$a_i = \sum_{p} w_{ip}^{s} S_p + \sum_{j \neq i} w_{ij}^{m} M_j - \theta_i \qquad \textbf{(5)}$$

Here, the input value of sensor p is defined as S_p (e.g., the sound volume and the visual moving area, etc.), the output of motor j is M_j, and the activity of motor i is a_i. The commands made to motor i are generated using a_i. In this architecture, the morphology of the behaviors depends on the weight value of w in which the descriptions are not explicit. The initial value of w depends on the physical arrangement of the motors and the sensor; i.e., w is a large value when the distance between the sensors and the motors is small. At this stage, a designer who observes the behaviors of WAMOEBA-2 adjusts w.

When the motor agent is used for the arm control, setting the weights of the network is difficult. We thought that the weight degrees were acquired by the feedback-error-learning method. [12] We considered the following two points in application and then composed the control algorithm.

1) There are neuron groups which code the "directions" in the surface layer of the motor area of the brain cortex, and there are neuron groups which code the "forces" in the deep layer.
2) The mechanical arm system is usually controlled by the speed command and not the torque command.

Fig. 5 describes the block diagram of the arm control. One is the motor agent which learns the motion direction. The other is the Back Propagation NN (BPNN) which learns the force information. (gravity compensation, etc.) x_r is the target trajectory and θ is the joint degree.

The arm system completed the learning of the BPNN and the motor agent by the reaching motion 3 or 4 times. The arm system learned basic motions such as trajectory followings, gravity compensation, etc.

Fig. 6 shows one example of the motions which the arm system acquired. Each joint degree and the errors of the end-effector position are shown in Fig. 7 and Fig. 8 respectively. This is an arm motion when a human contacted the arm system. At first, the arm kept the position of the hand of which the error is around 31 [mm]. When the contact force was given on a link between the #2 joint and the #3 joint, the #3 joint moved the hand toward the target direction, although the #1 and #2 joints moved to avoid the load torque. As the result of the motion, the position error converged under 30 [mm]. This is the peculiarity of the motion of the motor agent; that is, the decentralized and autonomous behaviors.

The hand target position of WAMOEBA-2R is the moving area position obtained from the camera image. For instance, the arm of WAMOEBA-2R approaches the waving human's hand etc. The hand of WAMOEBA-2R shuts when the object is detected by the photoelectric sensor, and opens when the FSR sensor detects more power than the threshold. Using these functions, WAMOEBA-2R can communicate with human beings by way of physical interactions such as a “handshake” etc.

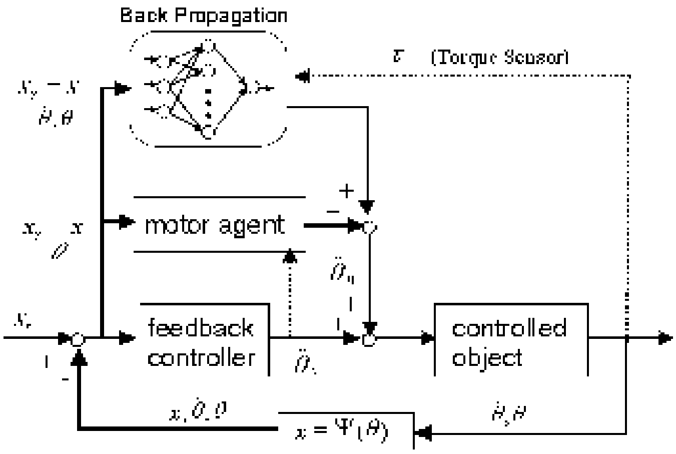

Fig. 5 Block Diagram of Wamoeba-2R Arm Control

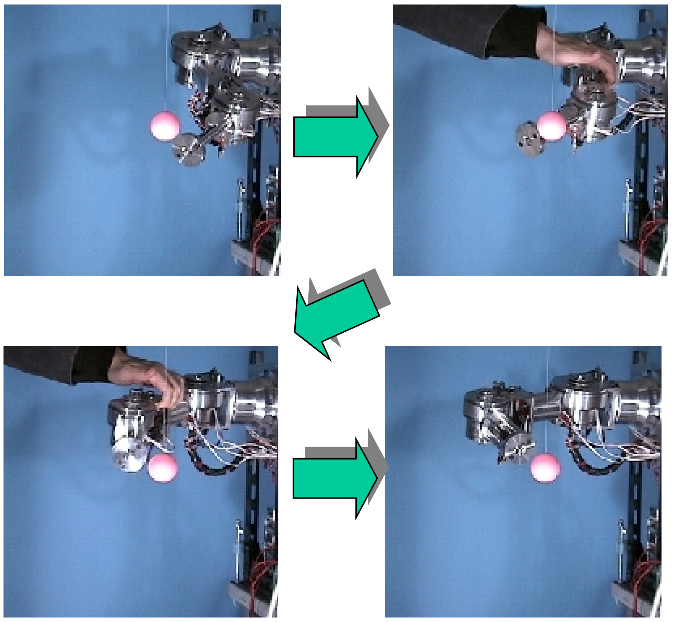

Fig. 6 Physical interaction between human and Wamoeba-2R arm

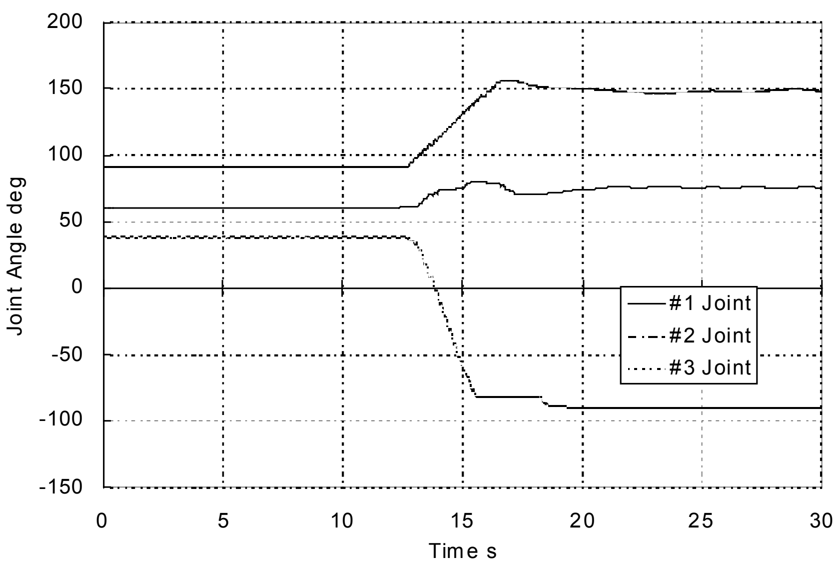

Fig. 7 Shoulder and Elbow Joint Angle

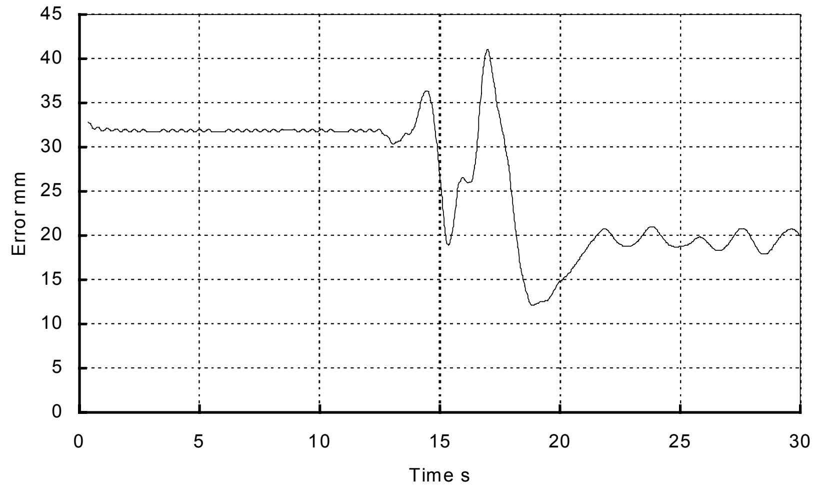

Fig. 8 Error of End Effector

5. Communication using WAMOEBA-2R

5.1 Emotional expression of WAMOEBA-2R

In this section, we outline the communication system between WAMOEBA-2R and humans in actual experiments. Humans can communicate with WAMOEBA-2R by hand waving, hand clapping, calling, handshake, and so on. WAMOEBA-2 reciprocates with various reactions, such as approaching, escaping, making sounds, eye tracking, and arm stretching. The motor agent generates these actions. In addition, WAMOEBA-2 changes the motion speed, volume/speed/loudness of sounds, and color output on LCD by hormone parameters.

5.2 Characteristics of communication

Most conventional emotion models have a limited ability to communicate with humans. Usually, a human being observes and judges the expressions of the emotion model, and the recognition rate is the evaluation of the model. In communication between WAMOEBA-2 and humans, there is no scenario like this. The psychological impressions in humans change dynamically according to the behavior of the robot and/or the humans. The characteristics of WAMOEBA-2 communication are as follows.

1) Adaptability in real world

Since WAMOEBA-2 is an independent and behavior-based robot, it is not necessary to standardize its environment. Since, there is no limitation for humans either in the standing position and/or in motion.

2) Diversity of the ways to communicate

Human beings can communicate without special interface tools. Moreover, neither "words" nor "gestures" for communication are specified, and preliminary knowledge is not required.

3) Development of communication

Communication is developed according to the behavior of humans and WAMOEBA-2 in real-time. There is no "story" and/or "scenario" set beforehand by a designer.

It is believed that the "freedom degree" mentioned above (where humans are not restrained in communication with robots) is an important element in order to realize robot-human emotional communication.

6. Questionnaire Experiment

We believe that experimental evaluation is indispensable in analyzing the emotional communication between human beings and robots, and demonstrations and questionnaire experiments were performed at the '99 International Robot Exhibition held at "Tokyo Big Site," Oct. 1999, with about 150,000 visitors. The objective of this experiment was to investigate the general psychological impressions of human beings when communicating with an autonomous robot.

Answers were obtained from 150 visitors, which involved many men (86%), students (32%), and engineers (11%). The generations consisted of people in their twenties (42%) and thirties (20%). The above percentages were based on the fact that the exhibition focused on industrial robots.

The experimental procedure was as follows: first, we explained the research background and the functions of WAMOEBA-2R to the subject operating the WAMOEBA-2R. Next, the subject actually interacted with the robot (Fig. 9) and then filled out the questionnaire. In this experiment, the voice recognition function and the face recognition function mentioned in 3.3 have not been used.

As a result of the factor analyzing of the 14 questions, 5 factors were obtained. Table 4 expresses the relationships between the questions and the factors.

- 1) Intelligence: "Intelligent or Unintelligent?" and "Does it recognize humans?"
- 2) Like: "Violent or Quiet?" and "Goodwill or Hostile?"
- 3) Humanlike: "Emotional or Unemotional?" and "Can it communicate?"
- 4) Contact: "Dull or Sensitive?" and "Do you want to touch it?"
- 5) Friend: "Do you want to be friends?" and "Like or Hate?"

Table 4 The result of the Factor Analysis

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
8 Intelligent or Unintelligent?	0.825049	0.258152	0.271626	-0.02702	0.046574
7 Does it recognize humans?	0.76268	0.101214	0.114833	-0.11771	0.044001
3 Intentional or Meaningless?	0.49389	0.099919	0.564898	-0.12058	0.108397
5 Animal-like or Machine-like?	0.446012	-0.34628	-0.21203	-0.47357	0.374937
14 Tame or Untame?	-0.40629	-0.52541	0.163873	-0.05558	-0.19268
10 Violence or Quiet?	-0.00451	-0.84393	-0.21612	-0.27376	-0.06163
12 Goodwill or Hostile?	0.286418	0.768223	0.060526	-0.04571	0.117891
1 Emotional or Unemotional?	0.126162	0.087847	0.947619	0.076843	0.042215
11 Can it communicate?	0.160235	0.192068	0.52762	-0.05644	0.107037
4 Dull or Sensitive?	0.225131	-0.06964	-0.01006	-0.88048	-0.02299
9 Do you want to touch it?	-0.27897	-0.18618	0.027783	-0.608	-0.19639
6 Do you want to be a friend?	0.052008	0.169049	0.097179	0.083048	0.96097
2 Like or Hate?	0.307823	0.263375	0.285189	0.04647	0.409472
13 Delicate or Cheek?	0.390676	0.076924	-0.03078	0.141832	0.107614

The first factor is "Autonomy" and the "Physical interaction" which is valued as a function of the arm-hand system, is the fourth factor.

Fig. 10 shows the results of the answers to the adjective pairs in the questionnaire concerning the second factor which is thought to be significantly related to "Friendliness." WAMOEBA-2R was generally rated with the impression of "Goodwill" and "Friendliness." It can be interpreted as "expectations" of the visitors to the autonomous robots expressed in the results.

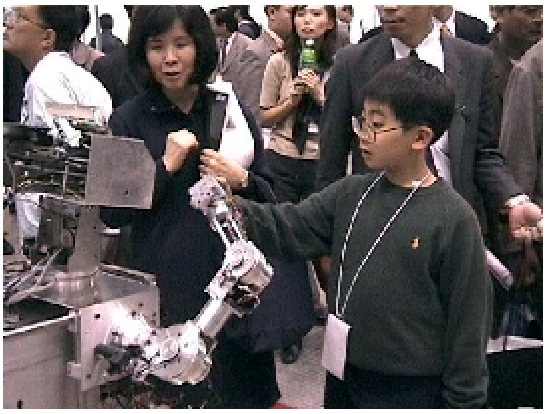

Fig. 9 Physical Interaction between a child and WAMOEBA-2R
(in '99 International Robot Exhibition)

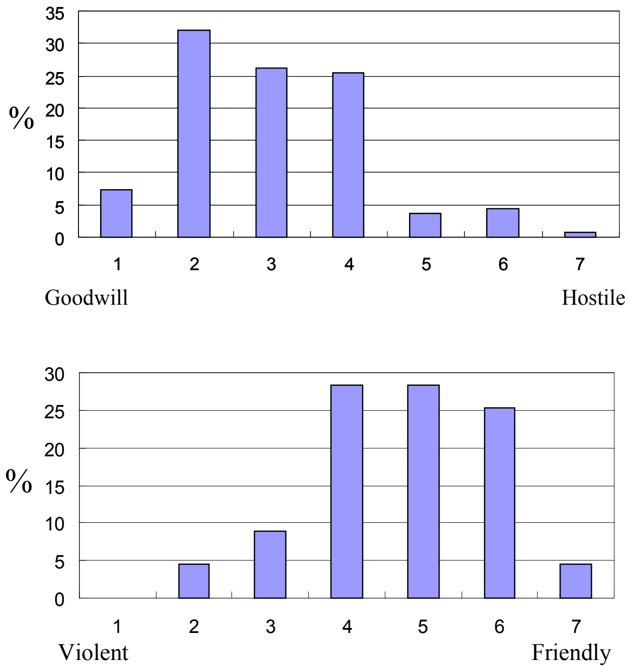

Fig. 10 Examples of the results of the Questionnaire

7. Conclusions and Further Research

This paper described the functions of the autonomous robot WAMOEBA-2R, such as the arm-hand system and the audiovisual system. In addition, the results of the questionnaire experiment carried out a '99 International Robot Exhibition were presented.

The communication between an autonomous robot and human beings discussed in this paper is a new concept which is different from the conventional robot-human communication which only focuses on the cost and efficiency. However, the autonomy and/or the intelligence of robots will progress further, and they will be used in homes and hospitals. Although the communication systems discussed here are indispensable, still need to be addressed, such as methods to maintain human-friendliness and human empathy to robots. It is expected that the communication experiment of the physical interaction between robots and humans shown in this paper demonstrate important findings for “human robot symbiosis” in the future.

In the future, the emotion model of WAMOEBA-2R will be optimized from the perspective of the types of hormone parameters and their effects. Since many comments were voiced concerning the “will” of WAMOEBA-2R in the questionnaire, it is thought that WAMOEBA-2R should be equipped with more intelligent functions for satisfactory human-robot emotional communication.

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