ON THE DEVELOPMENT OF THE EMOTION EXPRESSION HUMANOID ROBOT WE-4RII WITH RCH-1

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Abstract—. Among social infrastructure technologies, Robot technology (RT) is expected to play an important role in solving the problems of both decrease of birth rate and increase of elderly people in the 21st century, specially (but not only) in Japan where the average age of the population is rising faster than any other nation in the world.

In order to achieve this objective, the new generation of personal robots should be capable of a natural communication with humans by expressing human-like emotion. In this sense, human hands play a fundamental role in exploration, communication and interaction with objects and other persons.

This paper presents the recent results of the collaboration between the Takanishi Lab of Waseda University, Tokyo, Japan, the Arts Lab of Scuola Superiore Sant'Anna, Pisa, Italy, and RoboCasa, Tokyo, Japan. At first, the integration of the artificial hand RTR-2 of ARTS lab with the humanoid robotic platform WE-4R during ROBODEX2003 is presented. Then, the paper show the preliminary results of the development of a novel anthropomorphic hand for humanoid robotics RCH-1 (RoboCasa Hand No.1) and its integration into a new humanoid robotic platform, named WE-4RII (Waseda Eye No.4 Refined II).

Keywords: Humanoid robotics; personal robotics; artificial hand; human-robot communication; Emotional Expression.

1. Introduction

The average age of Japanese population is rising faster than any other nation in the world, and by the middle of the 21st century a third of the population is expected to be of age 65 or above. Simultaneously, the number of children born annually is dropping [1]. Italy as well is facing the same problem [2], even if with smaller numbers. In this scenario, there is considerable expectation that, among all social infrastructure technologies, next-generation Robot Technology (RT) will be invaluable in supporting this aging society, by creating robots capable to coexist with the human living environment, functioning not merely as technological tools but as partners and companions [3].

In order to obtain a successful interaction between humans and humanoid robots, particularly for home and personal assistance of elderly and/or handicapped persons, it is important that the personal robot is able to adapt to its partners and environment, and moreover that it is be able to communicate in a natural way with humans.

In this sense, the hand is a fundamental organ for exploration, communication and interaction with objects and other persons. The human hand, in fact, is a marvelous example of how a complex mechanism can be implemented, capable of realizing very complex and useful tasks using a very effective combination of mechanisms, sensing, actuation and control functions [5]-[7]. The human hand is not only an effective tool but also an ideal instrument to acquire information from the external environment. Moreover, it is capable of expressing emotions through gesture.

Developing a truly human-like artificial hand is probably one of the most widely known paradigms of "bionics". Roughly speaking, artificial hands could be divided into prosthetic hands and robotic hands. Prosthetic devices are simple gripper, with one or two DOFs, with high reliability and robustness, but with poor grasping capabilities [8]-[12]. Due to the lack of DOFs, such devices are characterized by a low grasping functionality. In fact, they do not allow adequate encirclement of objects, in comparison with the adaptability of the human hand. Conversely, several robotic hands have been developed in the last decades [13]-[15]. These hands have achieved good performance in mimicking human capabilities, but they are complex devices requiring large and bulky controllers [15]-[18]. Moreover, their weight and size in general prevent their application on current humanoid platforms.

The work described in this paper presents the recent results of the collaboration between 2 laboratories, the Takanishi Lab of Waseda University, Tokyo, Japan, and the Arts Lab of Scuola Superiore Sant'Anna, Pisa, Italy, that have created a joint laboratory in Tokyo for investigating the problems of human-robot interaction with an interdisciplinary approach. This joint laboratory is called RoboCasa, it is located in Tokyo, and it is promoted by the Italian ministry of Foreign Affairs.

At first, the integration of the artificial hand RTR-2 of ARTS lab with the humanoid robotic platform WE-4R (Waseda Eye #4 Refined) during ROBODEX2003 is presented. Then, the paper shows the preliminary results of the development of a novel anthropomorphic hand for humanoid robotics RCH-1 (RoboCasa Hand No.1) and its integration into a new humanoid robotic platform, named WE-4RII (Waseda Eye No.4 Refined II).

2. The first joint humanoid platform at ROBODEX2003

The primary objective of the RoboCasa team was to increase the expressional capabilities of the humanoid robot WE-4R (Fig. 1), developed in Takanishi lab [4] by adding new anthropomorphic hands. WE-4R in fact, has head, neck, trunk, lung and the arms with a total of 47 degrees of freedom. The system is able to react to the extrinsic stimuli assuming 7 facial expressions (Happiness, Anger, Disgust, Fear, Sadness, Surprise, and Neutral) and moving the head and the arms.

The first joint humanoid platform has been integrated in occasion of ROBODEX 2003, held in Yokohama, Japan, from April 3 to April 6, 2003. This humanoid robotic platform integrates the Emotion Expression Humanoid Robot WE-4R with the robotic hand RTR-2 developed at the ARTS Lab of Scuola Superiore Sant'Anna [17],[18] (Fig. 4).

The arms of WE-4R are anthropomorphic manipulators with 9 degrees of freedom (DOFs) and the head has 29 DOFs (waist: 2, neck: 4, eyeballs: 3, eyelids: 6, eyebrows: 8, lips: 4, jaw: 1, lung: 1) and a multisensory system which serve as sense organs (visual, auditory, cutaneous and olfactory sensation) for extrinsic stimuli [4]. This robot reacts to the extrinsic stimuli assuming the 7 basic facial expressions (happiness, anger, disgust, fear, sadness, surprise, and neutral) and accordingly moving the head, the body, and the arms [19]. However, the hands of this robot have a pure aesthetic function, and they cannot be used to express any gesture, to grasp objects, or actively explore the environment like humans do.

In order to overcome this limitation, the robotic hand RTR2 has been connected to WE-4R. This hand has three under-actuated fingers, with 9 DOFs in total, 2 of which are directly controllable (opening/closing of all fingers and thumb abduction/adduction). The adduction/abduction movements of the thumb enable the execution of several functional grasps, like cylindrical grasping and lateral grasping [18]. The sensory system is integrated within the hand structure and it is composed of exteroceptive (pressure sensor on the thumb) and proprioceptive sensors (position sensors, current sensors, and tension sensors) [21]. The main characteristics of the RTR2 hand are summarized in Table I.

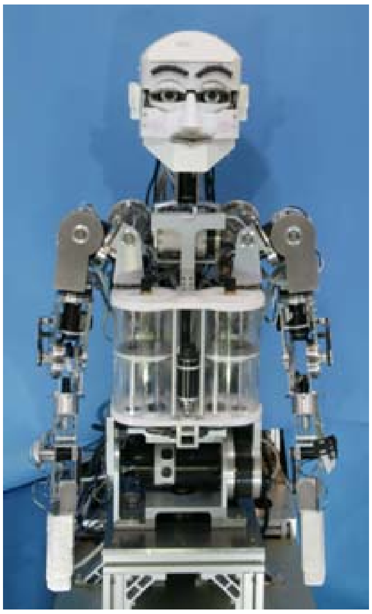


Fig. 1. The Emotion Expression Humanoid Robot WE-4R (Waseda Eye No.4 Refined) developed at Takanishi Lab.

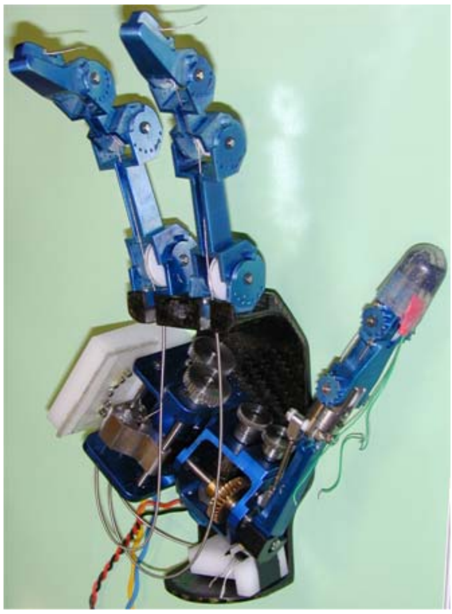


Fig. 2. The robotic hand RTR-2 developed at ARTS Lab.

Table I. Main characteristics of the RTR2 hand.

Number of fingers	3
Degrees of Freedom	9
Degrees of Motion	2 motors integrated into the palm
Underactuation level	7
Thumb ab/adduction	Yes
Weight	320 grams
Maximum grasping force	16N
Sensors	Current sensor x 2 Pressure sensor x 1 Tension sensor x 2 Position sensor x 2

The RTR2 hand is controlled by a laptop (ACER Travelmate 6xx, Win 2000 Pro) with a National Instruments PCI-6025E, 12-Bit, 16 Analog Input Multifunction acquisition board and SCB-68 Connector. The control software is developed in LabView 6.1 [22]. The hand control software exchanges data with the main control computer trough TCP/IP.

The expressions of the seven basic emotional patterns of this joint humanoid platform are showed in Fig. 3. Since only the right hand of WE-4R has been replaced with RTR-2, the right side of WE-4R could express the emotional difference by opening or closing its hand. However, the left side of the robot seemed to be a little bit stranger than the right side, because the left hand has a pure aesthetic function. Therefore, RTR-2 was effective to improve the emotional expression of the humanoid robot.

Moreover, WE-4R's behavior was limited because it couldn't grasp objects. On the contrary, WE-4R with RTR-2 could receive an object from a human partner, by using the CCD cameras on the WE-4R's head in order to coordinate the arm-hand movement. So, the integration of the robot hand could improve the robot behaviors or interactive motions.

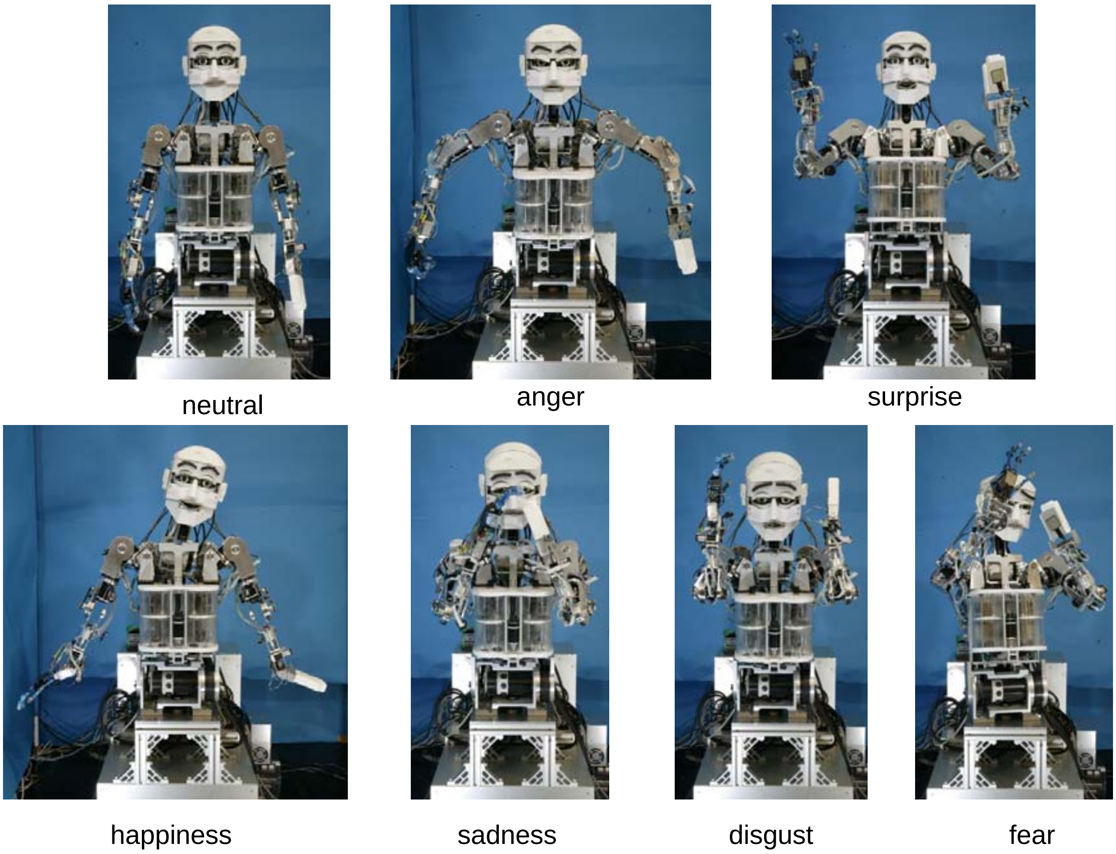


Fig. 3. The seven basic emotional expressions of the first joint ARTS-HRI humanoid platform.The presence of a three-fingered hand improves the expressivness of the robot.

3. Description of the new joint humanoid platform

In order to overcome the limitations of the first joint humanoid platform (Section 2) and to increase its performance, the forearms and the hands of the humanoid platform has been re-designed. According to the requirements defined in RoboCasa, the two hands has been designed and fabricated at ARTS lab. In particular, the new hands has been designed and realized in order to be capable of:

- **Basic gesture**, like pointing, waving (calling people), closed hand (fist), hand shake, closing mouth when yawn, goodbye, ok, good, peace sign, counting (from 0 to 5), and so on;
- different **grasping**, like cylindrical grasping (i.e. small bottle), spherical grasping (i.e. apple), tip pinch (i.e. candy), and lateral grasping (i.e. key), to carry on some basic activities like single hand grasping of small objects (apple, banana, can, small bottle, small toys and puppets, etc.) or 2 hands grasping of large objects, up to 20cm (i.e.: ball, and big toys and puppets).

Moreover, the hands should be capable of:

- Hardness measurement, like 2-hands measurement (by holding the object with the 2 hands), 1 hand measurement (by grasping the object), 1 finger measurement (by pressing the object against a hard surface);
- Surface recognition.

However, these two functionalities have not been yet exploited in the current prototype.

A picture of the prototype of the new humanoid platform, named WE-4RII (Waseda Eye No.4 Refined II) with the two novel anthropomorphic hands, named RCH-1 (RoboCasa Hand #1), is showed in Fig. 4. In the following section the detailed description of each part is presented.

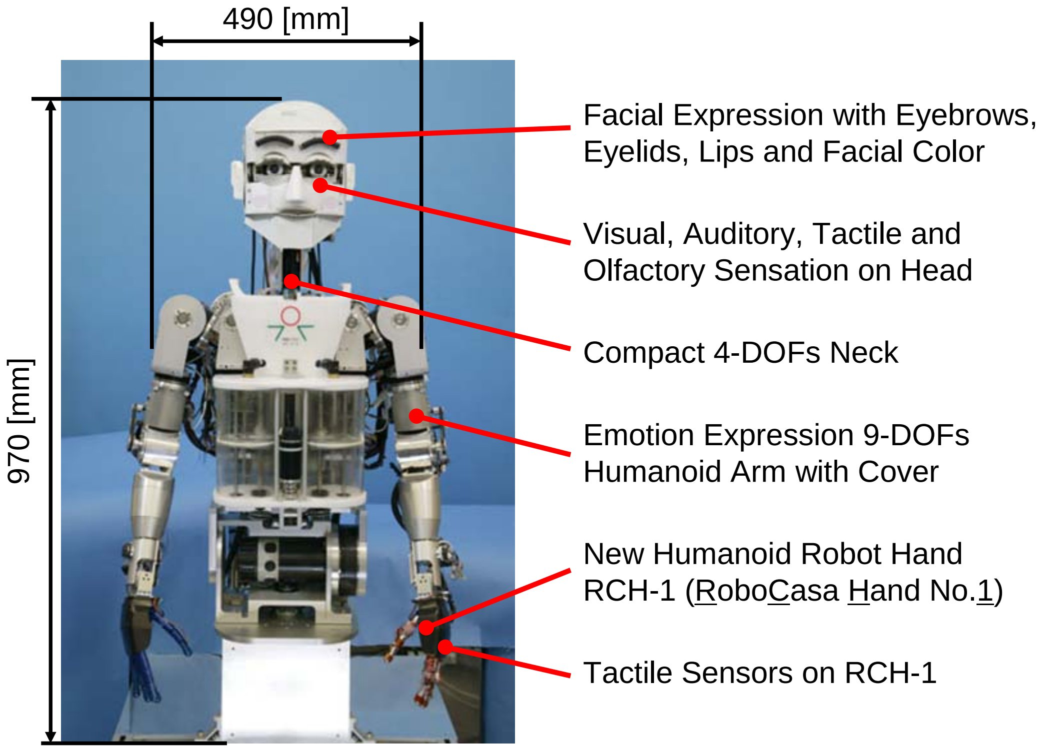


Fig. 4. A picture of the new humanoid platform WE-4RII with RCH-1, with the description of its main features.

3.1. ***Humanoid Robot Hand RCH-1***

In order to obtain these functionalities, the Hand System of the new humanoid platform should be composed by 2 symmetrical hands (left and right) with 5 fingers each. There should be 6 motors, one for opening/closing each finger plus one for abduction/adduction of the thumb. The thumb adduction/abduction motor could be located in the palm, while the other 5 motors should be located into the forearm.

The dimensions of this hand should be compatible with the standard Japanese adult male hand, i.e. weight lower than 500g and approximate size of 188x106mm, with length of the fingers of about 110mm and diameter of 20mm.

The speed of the fingers of the artificial hand should be comparable with the one of the human fingers, i.e. the maximum tapping frequency should be around 4.5 Hz and the maximum angular velocity should be around 2000 deg/s.

3.1.1. Description of the prototype

The new hand consists of 5 identical underactuated fingers with cylindrical phalanges in aluminum alloy. The design of the finger is based on the PALOMA Hand [24], which in turn is an evolution of the RTR2 hand [18]. A picture of the dorsal view and the palmar view of new hand are presented in Fig. 5.

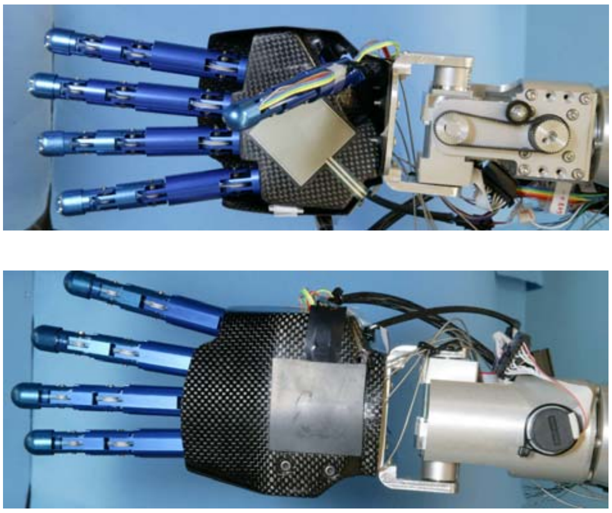


Fig. 5. Palmar (up) and dorsal (down) view of RCH-1.

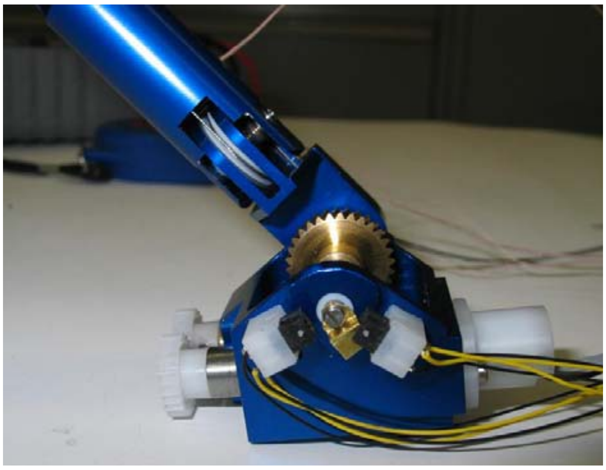


Fig. 6. Details of the thumb adduction/abduction mechanism.

RCH-1 has in total 16 Degrees of Freedom (DOF)/6 Degrees of Motion (DOM), 1 DOM/3DOFs for each finger (flexion/extension) plus one DOM for thumb positioning (adduction/abduction). A 2-DOFs trapezo-metacarpal joint at the base of the palm allows the thumb opposition movement towards the other fingers (Fig. 6).

Table II. Mechanical characteristics of RCH-1

Number of fingers	5
Degrees of Freedom	16
Degrees of Motion	6 (1 motor integrated into the palm, the other 5 integrated into the forearm)
Underactuation level	10
Thumb ab/adduction	Yes

Weight	320 grams
Maximum grasping force	30N (expected)
Dimensions:	
Total Lenght	191 mm
Lenght of fingers	92.2 mm
Diameter of fingers	14 mm
Palm width	95 mm
Palm thickness	40 mm

Each finger is underactuated, and its movement is driven by a single cable actuated by a motor. The motor for thumb adduction/abduction is located inside the palm, while the motors for the movement of the fingers are all located inside the forearm, thus mimicking the structure of the musculoskeletal system.

The palm is composed by and outside shell, made in carbon fiber, divided into dorsal part and palmar part, and an inside frame, which holds the fingers and contains the thumb abduction/adduction transmission chain. Optionally, a soft padding made by silicon rubber can be mounted on the palm in order to increase the compliance of the grasping. The total weight of the hand is about 320 grams, excluding the motors in the forearm and the cosmetic covering of the palm.

RCH-1 is capable of several grasping patterns. Some examples are shown in Fig. 7. From top left, clockwise: lateral grasping, thumb-middle opposition, three-digital grip, self-adaptation to the grasped object, thumb-middle opposition again, and thumb-index opposition.

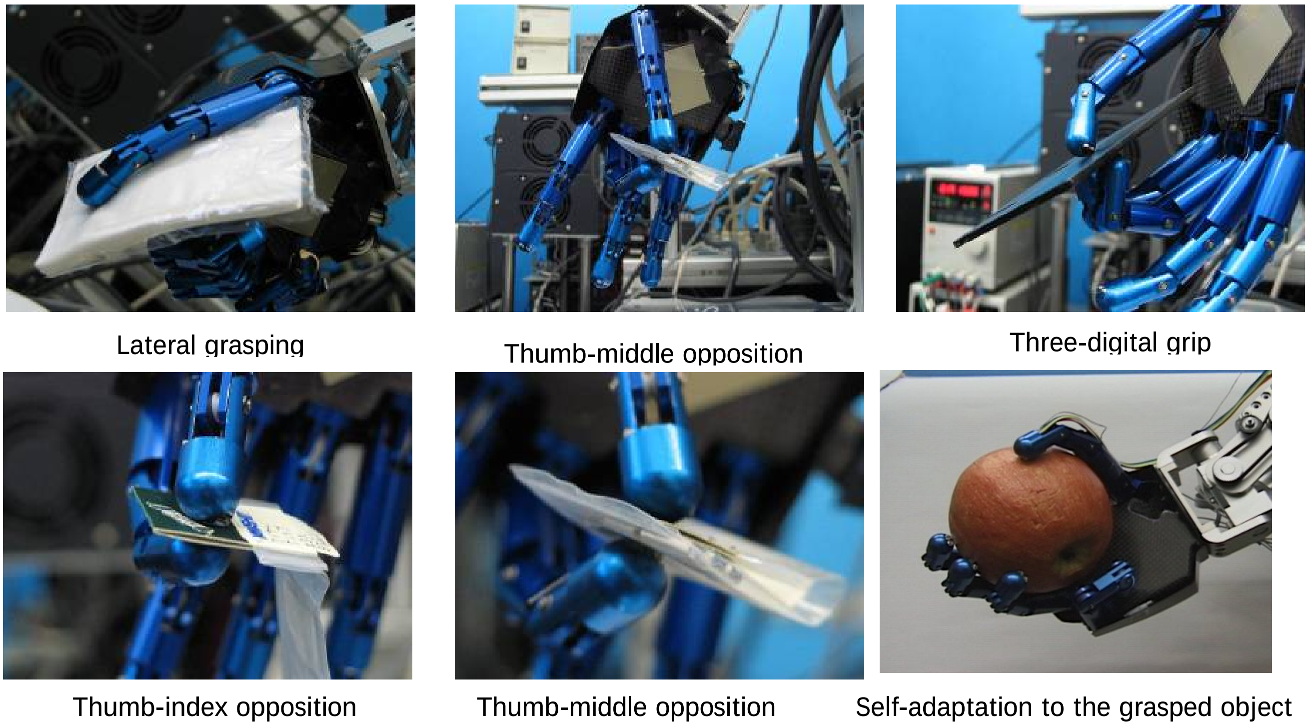


Fig. 7. Demonstration of some of the grasping capabilities of RCH-1.

3.2. ***Sensory system of the RCH-1***

The RCH-1 hand is equipped with several tactile sensors. In particular, it has:

- 17 contact sensors (on/off sensors), on the palm (2) and on all the phalanges (1 for each);
- Two 3D force sensors, integrated into the fingertip of the thumb and of the index finger
- One FSR sensor, on the dorsum of the hand.

In addition, each motor has its own encoder for position control of the movement of the fingers. The description of these sensors is presented in the following paragraphs.

3.2.1. Contact sensors

Contact sensors provide information to the tactile sensing system that adequate contact or release information has been established for further manipulative actions. The contact sensors for the RCH-1 were constructed using flexible circuits and were fabricated with the standard photolithography procedures on kapton (polyimide sheets). The top and bottom kapton sheet (Dupont Pyralux film LF9150R) are 127µm thick having a single-sided copper cladding of 305 g/m^2 Cu with approximately 35µm thickness.

Each of the distal, middle and proximal phalanges has large copper areas for contact. Once assembled, the top and bottom layers touch each other when a sufficient force is applied. Strips of polyurethane foam with an approximate thickness of 1mm are positioned on the bottom layer. The foams function as springs to make the top kapton layer return to its initial state upon the termination of contact with an object. Without these foam strips, severe hysteresis was observed. Furthermore, this “unnecessary contact” becomes more evident when the layers are wrapped around the robot’s fingers.

Efforts were made to make these sensors more sensitive to contact to emulate the mechanoreceptors of the human hand. Johansson [25] estimated that 90% of the Slowly Adapting I (SAI) and Fast Adapting I (FAI) mechanoreceptors get excited to a stimulus of 5 mN and all of these react to an indentation of 1mm. Therefore, the

SAI mechanoreceptors, which have small receptive fields and adapt slowly to a stimulus, can be analogous to on-off contact switches in an engineering implementation.

A picture of the RCH-1 with the contact sensors is showed in Fig. 8 (left).

Fig. 8. RCH-1 with the contact sensors (left) and the FSRs (right) in evidence.

3.2.2. 3D Force sensors

The first version of the 3D force sensor is based on flexible structure with a cross disposition of the strain-gauges located at the base of the fingertip so as to make the whole fingertip a 3-component force sensor. Three strain gauges are used in order to sense the force on the 3 main axes, and other 3 strain gauges are used for temperature compensation. The performances of the 3D force sensors are summarized in Table III.

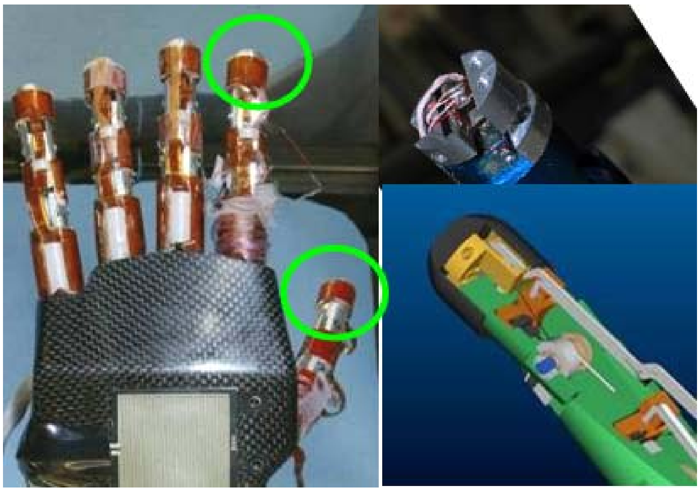


Fig. 9. The 3D force sensor mounted in the fingertip of the thumb and index finger (top right: detailed picture of the sensor; bottom right: 3D model of the structure of the finger, with the sensorized structure in evidence).

Table III. Performance of the 3D force sensor.

Maximum Force (N)		Sensitivity (mV/N)	
Fx max	4.62	Sens_x	0. 68
Fy max	5.96	Sens_y	1.2
Fzmax	4.62	Sens_z	0.66

3.2.3. FSRs on the dorsum of RCH-1

Two FSRs (Force Sensing Resistors) model 406 [26] have been put in stack on the dorsum of each hand. Despite of their poor accuracy, which ranges from approximately ± 5% to ± 25%, FSRs can be used to detect 'stroke', 'hit', and 'push' [27]. A picture of the hand with the FSR in evidence is shown in Fig. 8 (right).

3.2.4. Software & acquisition hardware of RCH-1

The personal computer used to control the hand system is an Intel PIII 1GHz with 512Mb RAM, Win 2000. This computer is connected by Ethernet to PC1 (Pentium IV 3GHz, Windows XP) used for image processing and PC2 (Pentium IV 2.6GHz, Windows XP) for sensory processing and motor control.

The exchange of data between the computer and the two hands is carried out by the following acquisition boards:

- 2 Analog acquisition boards (AD12-16 (PCI)E, CONTEC [29])
- 1 digital I/O board (PIO 32/32T, CONTEC)
- 1 analog output board (DA12-16 (PCI) , CONTEC)
- 2 boards for the acquisition of the data from encoders (PCI 6205C, Interface Corporation [30])

Each hand has 6 motors in total, 5 for the opening/closing of the fingers and 1 for the thumb abduction/adduction. The motor drivers used are TITech Driver Ver.2 [32].

The motors for opening and closing the fingers are Maxon RE-max17 4.5W 216012, with Gear GP16A 110323 and Digital MR Encoder 201940 [31]. The motor for the thumb ab-adduction is a Faulhaber 1016M006G, with planetary gearheads 10-1 64:1 and Encoder 30B19 [32]. The control software is developed in Borland Visual C++6.

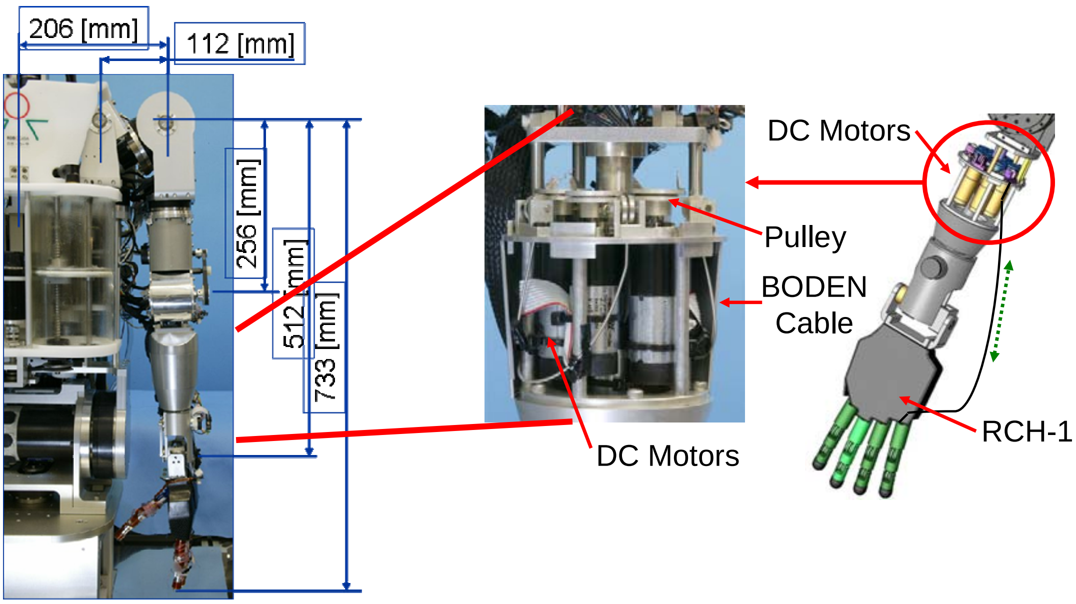


Fig. 10. The arm of WE-4RII (left), with the detailed view of the foreasm and of the position of the motors in it (right).

3.3. ***Integration of RCH-1 into WE-4R: development of a new forearm***

In order to integrate RCH-1 into WE-4R, the actuation system for extension and flexion of RCH-1 has been mounted inside the forearm of WE-4RII (Fig. 10), thus mimicking the position of *flexor digitorum* and *extensor digitorum* in the human forearm. The motors are connected to the fingers by using thin wires inside Bowden cables, thus mimicking the natural tendon system.

In WE-4R, the wrist joints were driven by DC motors with planetary gear system. So, the hand motion of WE-4R wasn't stable because of too much backlash. Considering that we had to redesign the forearms to mount the finger's motors, we changed also the wrist gear system to small harmonic drive systems in order to reduce the backlash and to miniaturize the wrist mechanism. In particular, we designed the link mechanism shown in Fig. 11 for the pitch axis of the wrist. The link mechanism transmits the motor power with the two links, which were supported by four ball bearings to reduce the slant caused between inner and outer rim.

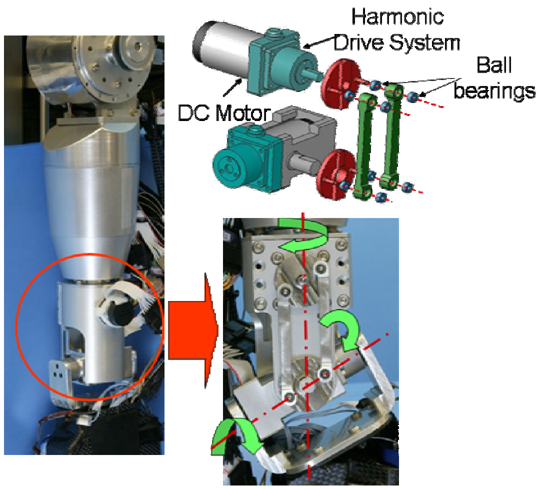


Fig. 11. Detailed view of the wrist Mechanism of WE-4RII

*3.4. **Sensors on WE-4RII***

Besides the sensors on the hand, WE-4RII has also visual, auditory, tactile and olfactory sensors on its head. A summary of the sensory system of WE-4RII, including sensors on the hands, is presented in Table IV.

Regarding visual sensor, WE-4RII has two color CCD cameras (CS6550, Tokyo Electronic Industry Co. Inc.) in its eyes. WE-4RII calculates the gravity and area of the targets. And, it can recognize any color as the targets and it can recognize eight targets at the same time. WE-4RII also can recognize the distance of the targets using the angle of convergence between the two eyes. If there are multiple target colors in the robot's view, WE-4RII follows the target which is autonomously selected by the robot in a 3D space.

Regarding auditory sensor, WE-4RII has condenser microphones (BL1994, Knowles Electronics Japan) in each ear. It can localize the sound direction from its loudness and the phase difference in a 3D space. For olfactory sensation, we set four semiconductor gas sensors (SB-19, SB-30, SB-AQ1A and SB-E32, FIC Inc.) in WE-4RII's nose. WE-4RII can quickly distinguish the smells of alcohol, ammonia and cigarette smoke. And, WE-4 has tactile and temperature sensations.

For tactile sensation, we used FSRs [26] and set them on the cheeks, forehead, top of the head and side of the head of WE-4RII. WE-4RII can recognize the difference in touching behaviors such as "push," "hit" and "stroke".

For the temperature sensation, we used a thermistor and a heat sheet, and we set them on the forehead [33].

Table IV. Sensors on we-4RII.

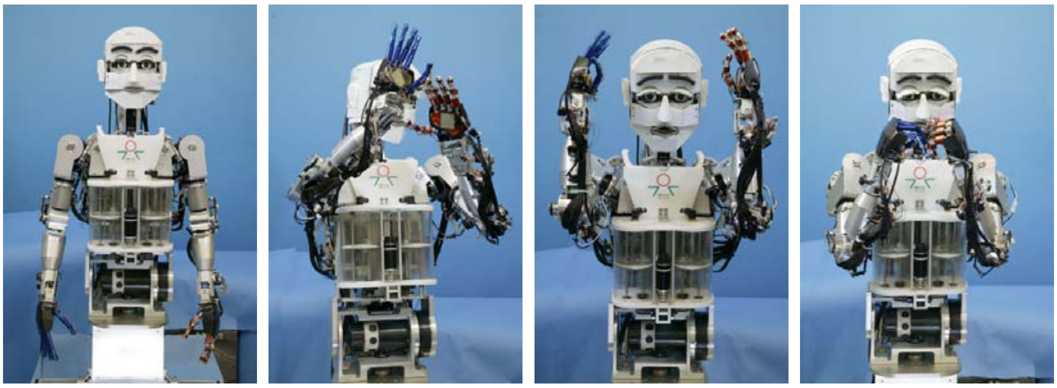
Part	Sensation		Device	Quantity
Head	Visual		CCD Camera	2
	Auditory		Microphone	2
	Cutaneous	Tactile	FSR	26
		Temperature	Thermistor	1
		Weight	Current Sensor	2
	Olfactory		Semiconductor Gas Sensor	4
Hand	Cutaneous	Tactile	Contact Sensor	16
		Tactile	FSR	4
		Force	3D Force Sensor	2

Table V. DOF Configuration of WE-4RII

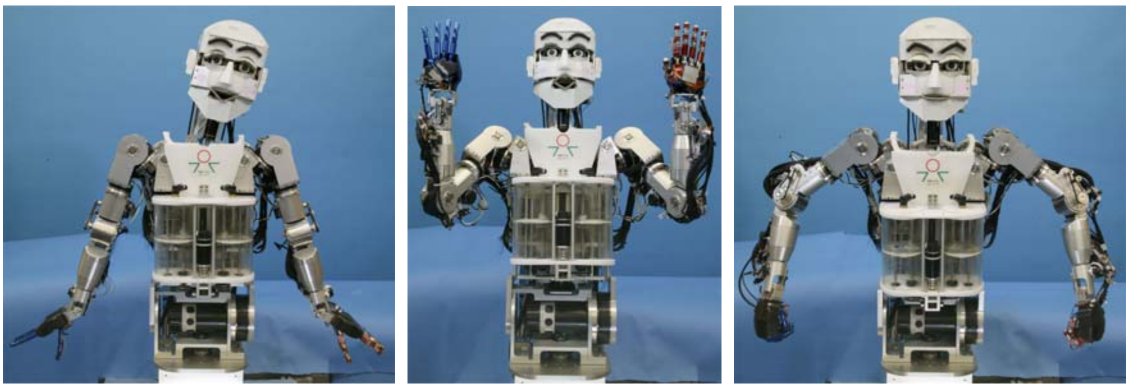
Degrees of Freedom	
Part	**DOF**
Neck	4
Eyes	3
Eyelids	6
Eyebrows	8
Lips	4
Jaw	1
Lung	1
Waist	2
Arms	18
Hands	12 (32)
Total	**59 (79)**

3.5. ***Emotional Expressions***

WE-4RII could express its emotion using the upper-half body motion including the facial expression, arms, hands, waist and neck motion. And, we considered that the motion velocity was as important as the posture in emotional expression. Therefore, we controlled both the posture and the motion velocity to realize the effective emotional expression. For example, WE-4RII moves its body quickly during the expression of “surprise”, but it moves its body slowly while expressing “sadness”. Fig. 12 shows the seven basic emotional expressions exhibited by WE-4RII.



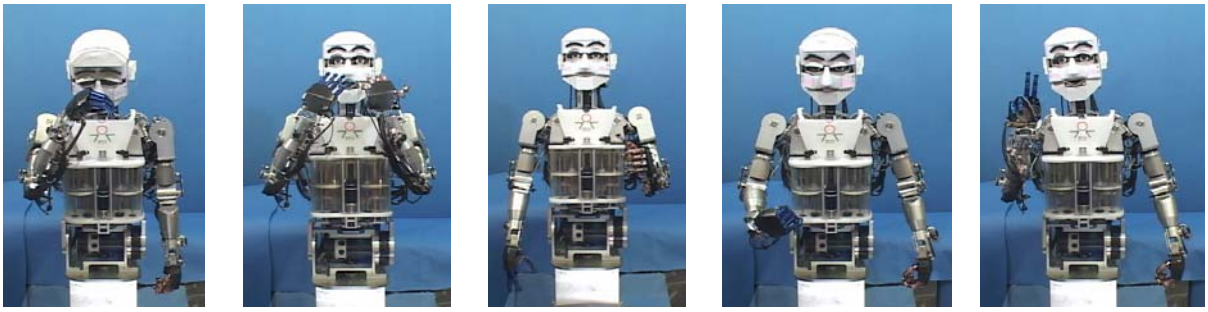
(a) Neutral (b) Disgust (c) Fear (d) Sadness



(e) Happiness (f) Surprise (g) Anger

Fig. 12. The seven basic Emotional Expressions of WE-4RII.

The robot is also capable of several other expressions, taking advantage of the expressivity of the hands. Some new pattern are presented in Fig. 13. The result of the evaluation of the recognition rate for the vasic expressions and for the new expressions are presented in section 4.3.



(a) pattern 1 (b) pattern 2 (c) pattern 3 (d) pattern 4 (e) pattern 5

Fig. 13. Some additional Emotional Expressions of WE-4RII.

3.6. ***Behavior and interactive motion of WE-4RII***

We improved the behavior and interactive motion of WE-4RII using its hands and the co-operating motion with visual sensation.

At first, WE-4RII calculates the position of the human face, the human hand or the target in a 3D space using the visual sensation on the head. Then, WE-4RII autonomously moves its arms and hand to interact to the partner. For example, WE-4RII could receive an object from a human partner and give the objects to the partner using its hands. Moreover, the WE-4RII could shake its hand with the partner following the partner’s face with its eyes and head.

On the other contrary, we also increased the robot behavior. We gave the robot motion patterns as the robot behaviors. WE-4RII autonomously selects its behavior according to the situation. To make the motion pattern, we have to define the positions, postures and time of the tip of the robot hands, and calculate the hand trajectory with 3D spline function. Then, the trajectories were divided in each 33 [ms]. The robot calculates the joint angle from divided trajectory using the inverse kinematics [19]. Because WE-4R had the same movable range as human, WE-4RII could output human-like motions by defining the motion patterns. We defined the various patterns such as throwing a ball and shaking a maraca.

3.7. ***Configuration of the Total System***

Fig. 14 shows the total system configuration of WE-4RII. We used three computers (PC/AT compatible) connected by Ethernet. PC1 (Pentium 4 3.0 [GHz], Windows XP) captures the visual images from CCD cameras and it calculates gravity and brightness of the target, and sends them to PC2. PC2 (Pentium 4 2.6 [GHz], Windows XP) obtains and analyzes the outputs from the olfactory and cutaneous sensations using 12 [bit] A/D boards and the sounds from microphones using a soundboard. Then, PC2 determines the mental state. In addition, PC2 controls DC motors excepting RCH-1. Then, PC2 sends control information of RCH-1 to PC3. PC3 (Pentium III 1.0[GHz], Windows 2000) obtain and analyze the sensor information of RCH-1 and control DC motors on RCH-1. PC3 sends the sensor information to PC2.

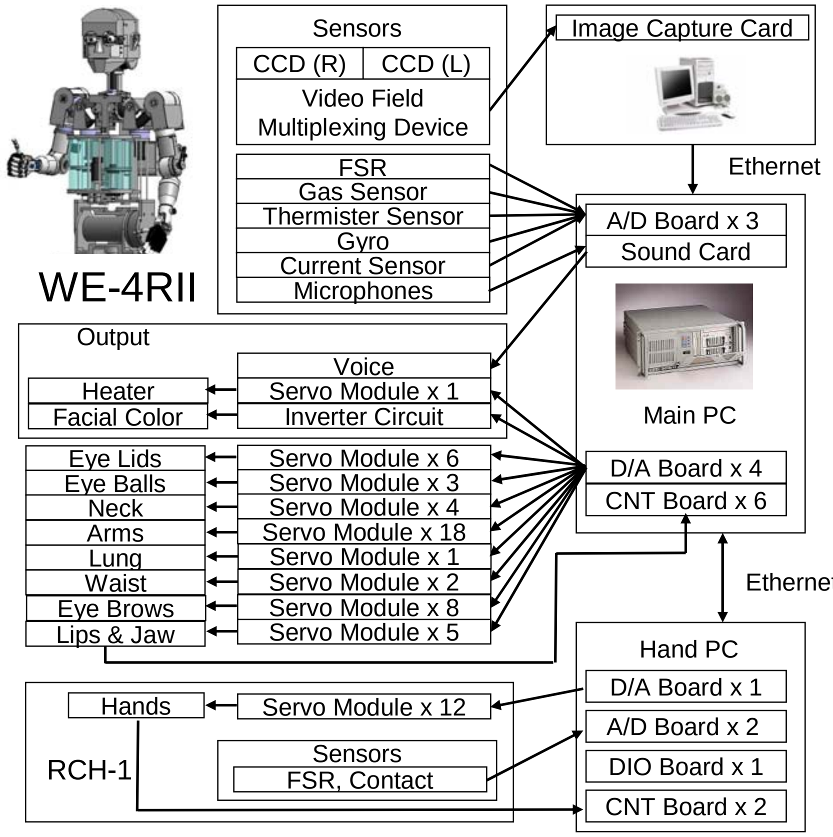


Fig. 14. Overall configuratio of the system.

4. Evaluation of the performance of the new humanoid platform

In order to assess the characteristic of the new humanoid platoform, three sets of experiments have been carried out:

- Exp 1: measurement of the speed of the movement of the phalanges;
- Exp 2: assessment of the expressiveness of gesture;
- Exp 3: evaluation of the recognition rate of the emotional expression of WE-4RII.

*4.1. **Exp 1: measurement of the speed of the movement of the phalanges***

The movement of the finger from the full extended position to the full flexed position (Fig. 15) has been recorded by using Photron PCI Fastcam high-speed video camera system (250 frames/sec, 512x480 pixel) [35]. The variation of the angular position vs. time (showed in Fig. 16) is measured using Photron Motion Tools™ software, and the instant angular speed is showed in. Fig. 17.

The maximum speed of the phalanxes is comparable with the maximum speed measured for the human hand with the same experimental framework. In particular, the maximum speed of RCH-1 is equal or greater to the the maximum speed of the human hand during the normal gesture activities, generally much slower than the maximum absolute speed. These data are summarized in Table VII.

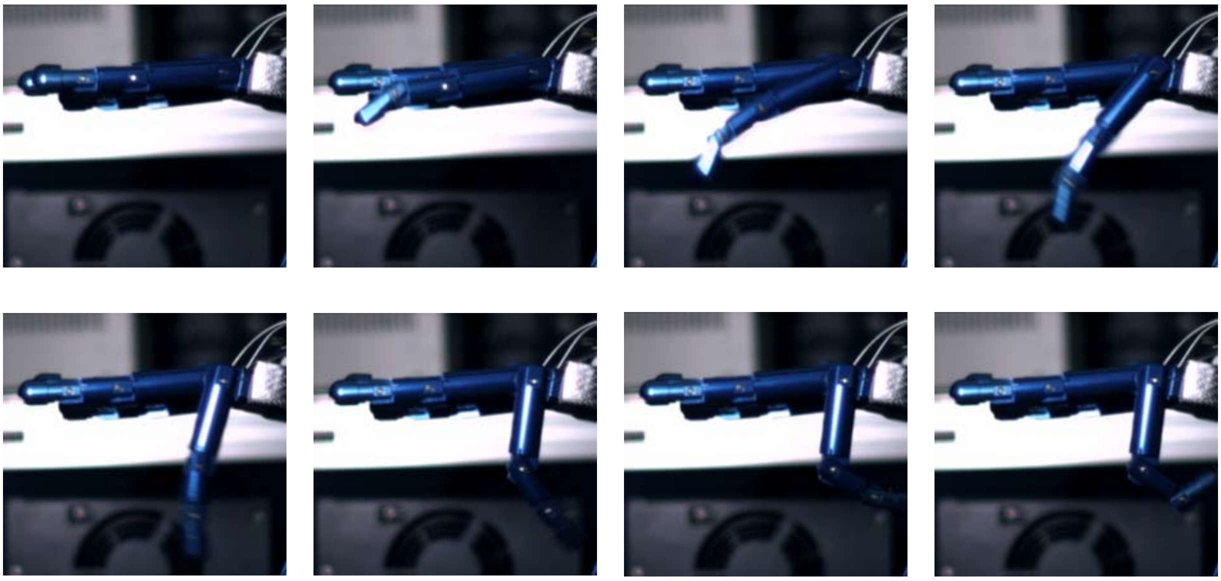


Fig. 15. Evaluation of the maximum speed of the phalanges of RCH-1 by tracking the position of the joints of the finger with a Photron PCI Fastcam high-speed video camera system.

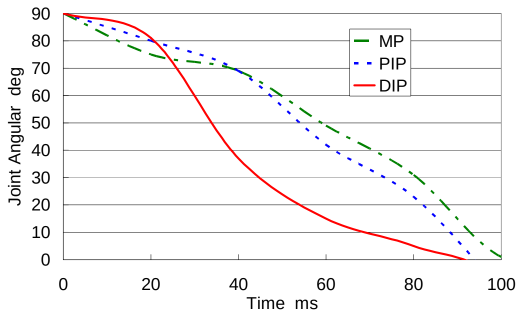


Fig. 16. Angular position of each phalanx of the index finger during a full closure.

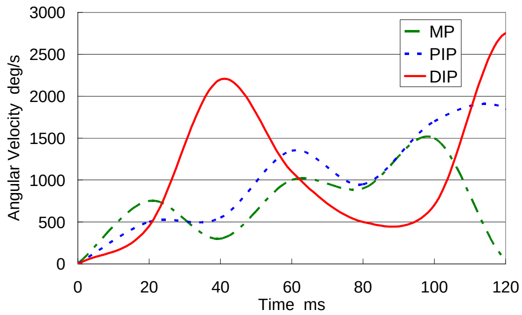


Fig. 17. Angular speed of each phalanx of the index finger during a full closure.

Table VI. Maximum angular speed (deg/s) in RCH-1 and in human hand.

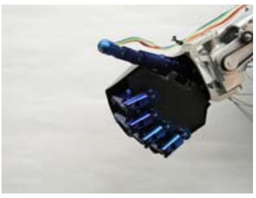
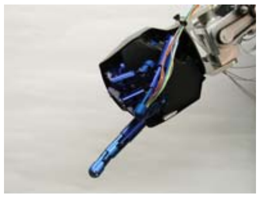
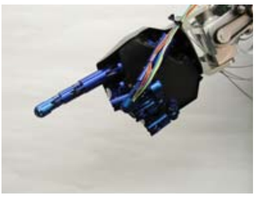
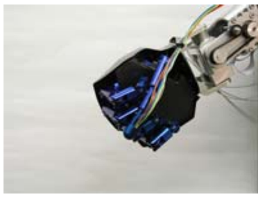
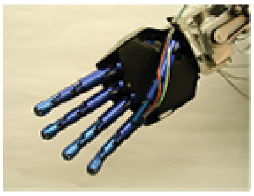
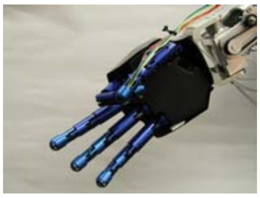
	Human (deg/s)	Human (deg/s) during emotion expression	RCH-1 (deg/s)
MP	2000	1000	1500
PIP	3750	1620	1850
DIP	3750	1750	2750

*4.2. **Exp 2: assessment of the expressiveness of gesture***

A second test has been carried out in order to assess the gesture capabilities of RCH-1. A set of pictures of the hand has been shown to a group of 14 people (average age: 21; sex: male), and their answers has been recorded. Their response is shown in Table VII.

As the responses show, each gesture could be interpreted in several different ways, depending on the context, the mood and experience of the observer, the sequence of gestures, and so on. Therefore, the hand is effectively capable of communicating different expressions and emotions according to its movements and its shape.

Table VII. Some gesture by RCH-1 and their interpretation by a group of 14 students.

	Ok: 14		Lovers: 7 Engagement: 7
	Number one: 7 To point: 7		Janken (“rock-paper-scissors” game): 13 Aggressiveness: 1
	Peace sign: 9 Number two: 2 Victory: 2 To smoke: 1		Number four: 10 To cut: 3 Karate: 1
	OK: 9 Money: 3 Number three: 2		

4.3. ***Exp 3: Evaluation of the recognition rate of the emotional expression of WE-4RII***

We evaluated the recognition rate of the emotional expression of WE-4RII. We showed 18 subjects (averaged age: 21; sex: male) the movies of the six basic emotional expressions exhibited by WE-4R and WE-4RII. In the movies, the expressions of WE-4RII and WE-4R were the same excepting the hand motion. WE-4RII expressed the postures shown in Fig. 12. Next, the subjects chose an emotion that they thought the robot expressed. Then, we examined the recognition rates of those emotional expressions. Finally, we compared the recognition rates of WE-4RII to WE-4R. The results of the experimental evaluation are presented in Fig. 18.

As a result, the recognition rate of “Happiness” facial expression was 5.5 points higher than WE-4R. And, all subjects correctly recognized the “Surprised”, “Sadness”, “Anger” and “Disgust” emotional expressions. However, the recognition rate of the “Fear” was 5.5 points lower than WE-4R’s rate because the some subjects considered the “Fear” emotional expression as “Disgust” emotional expression. In total, the averaged recognition rate of all emotional expressions of WE-4RII was 2.8 points higher than the WE-4R’s averaged recognition rate. As described before, the difference between emotional expressions of WE-4RII and WE-4R are only hand motion. Therefore, we considered that the RCH-1 had effective emotional expression ability. And, we also considered that these emotional expressions except “Fear” emotional expression were sufficiently effective.

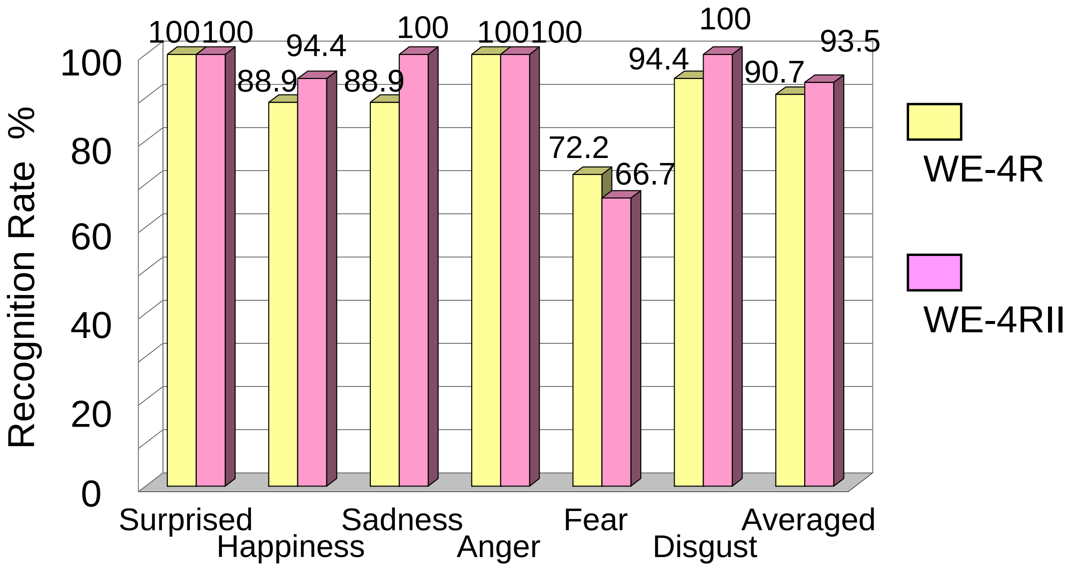


Fig. 18. Experimental Evaluation of the recognition rate of the emotional expression of WE-4R and WE-4RII.

4.3.1. Exp 3b: Evaluation of the recognition rate of the additional emotional expression of WE-4RII

Normally, people could express the same emotion in several different ways, according to several internal and internal conditions. Therefore, we defined several extra emotional patterns (Fig. 13), and we measured the recognition rate of them by applying the same experimental protocol as before. The experimental results are shown in Table VIII. The subjects felt the particular emotion to pattern 1, 2, 4 and 5. But, they answered that pattern 3 could have several emotions or meanings according to the situation. Therefore, we confirmed that WE-4RII could express its emotions in several different ways by using its facial expressions, neck, arms, hands and waist motion.

Table VIII. Experimental result of the additional emotional expressions.

	Anger	Happiness	Surprise	Disgust	Sadness	Fear	Other
Pattern 1	0	0	0	0	91.7	0	8.3
Pattern 2	0	0	91.7	0	0	0	8.3
Pattern 3	0	25	0	0	0	0	75
Pattern 4	100	0	0	0	0	0	0
Pattern 5	0	75	0	0	0	0	25

5. Discussion and Conclusions

In order to enhance the communication between robot and humans, two novel humanoid platforms has been realized. The first one, exhibited during ROBODEX2003 in April 2003, integrated the humanoid platform WE-4R, developed in Takanishi Lab of Waseda University, with the RTR2 Hand, developed by ARTS lab of Scuola Superiore Sant'Anna in collaboration with INAIL RTR Center. The preliminary results showed that the presence of a functional hand positively affected the capability of emotional expression of the robot.

For the second humanoid platform, two new artificial hands, named RCH-1 (RoboCasa hand #1), and two new forearms has been designed realized with a joint effort of the ARTS Lab, Takanishi Lab and RoboCasa. This new Emotion Expression Humanoid Robot, named WE-4RII (Waseda Eye No.4 Refined II), has been evaluated through the experiments and trough questionnaires, thus confirming that RCH-1 and WE-4RII had effective emotional expression ability.

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