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Paper:

Development of Whole-Body Emotional Expression Humanoid Robot for ADL-Assistive RT Services

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Personal robots and Robot Technology (RT)-based assistive devices are expected to play a substantial role in our society largely populated by the elderly; they will play an active role in joint works and community life with humans. In particular, these robots are expected to play an important role in the assistance of the elderly and disabled people during normal Activities of Daily Living (ADLs). To achieve this result, personal robots should better be capable of making emotional expressions like human. In this perspective we developed a whole body bipedal humanoid robot named KOBIAN that is capable of expressing human-like emotions. In this paper we present the development and evaluations of KOBIAN.

Keywords: humanoid robot, emotional expression

1. Introduction

In today's rapidly aging society with fewer children in Japan [1, 2], demands for devices or services based on Robot Technology (RT) are increasing in order to cope with the declining workforce or to realize a safe and secure society or affluent life. In the future, RT-based service industry to support daily living activities of elderly people is expected to grow and flourish substantially.

Robotics services to support daily living activities are services that can support a variety of daily activities with RT. Specifically, robots as physical agents autonomously fulfill supportive tasks by recognizing surrounding environments and receiving orders through natural communication. Such service robots need to be able to travel, handle things, recognize environments and be safe in providing physical support, to be able to communicate in the same way as humans do so not to impose extra strain on humans for psychological support and to provide reassurance.

For such service robots, we have proposed biped humanoid robots capable of emotional expressions and have conducted from 2006 through 2009 a commissioned research on "Development of RT-Based Systems to Support Comfortable Lifestyle" as a part of NEDO's Strategic Advanced Robotics Element Technology Development Project – Area of Service Robots – RT-Based Systems for Communication with Elderly People. The project focused on a study for basic element technologies for RT-based service systems that provide support services to users based on the structured extent of environmental information, and its preparedness such as RFID tags, environmental maps and so on as well as to promote robots to appropriately communicate with users in indoor living environments based on their individual differences such as age or gender, also targeted to make a prototype system to demonstrate the outcome of the studies.

The above-mentioned development project is divided into seven technical areas as follows: (1) adaptive communication technology; (2) technology to generate facial expressions of robots as new media; (3) acoustic treatment technology with centralized microphone; (4) technology to recognize people from all directions and record their behaviors; (5) technology to structure environmental information; (6) technology to integrate these element technologies for organically integrated use; (7) prototype system to implement the above-mentioned technologies (1) to (6) and demonstrate in indoor living environments.

For the prototype robot referred to in (7) above, we have developed a humanoid robot named KOBIAN [3]. KOBIAN, a biped humanoid robot capable of whole-body emotional expressions, has a head capable of facial expressions, two hands molded of soft materials, and a trunk and two lower limbs developed on WABIAN-2 [4].

This paper is to report on the development of KOBIAN and its evaluations.

2. Emotional Expression Humanoid Robot

We consider that the most appropriate form of communication required of robots that behave to orders by humans in the indoor living environments is the same form of communication that humans perform. Humans generally communicate with verbal information but in fact non-verbal information plays a more influential role than verbal information. Non-verbal information includes facial expressions, lines of sight, bodily motions and paralanguage, among which facial expressions play the most significant role [5]. Facial expressions represent emotions, and according to P. Ekaman happiness, sadness, anger, disgust, surprise and fear are the six basic emotions and the emotional expressions have cultural universality [6, 7].

We have focused our attention on the above-mentioned capability of emotional expressions and set one that is familiar to human users as requirements for the prototype robot system. In setting such emotional expressions as requirements, it is crucial to decide how far robots should resemble humans in appearance. Ishiguro, Kobayashi et al. explored resemblance to humans in developing android robots [8, 9] but it has been reported that when the likeness to human reaches a certain level, such robots present a sharp drop in familiarity to cause an "uncanny valley" phenomenon [10]. That suggests that it is not always the best solution to make robots to look exactly like a human. Even if we succeed in making hardware of robots looking exactly like humans, their similarities other than the appearance like behavior may present some negative impressions, and it would be difficult to bring these similarities infinitely close to humans. Miwa et al. developed a humanoid robot WE-4 [11] with simplified human appearance and exaggerated facial expressions that correspond to emotions or emotional expressions familiar to humans.

WE-4, a platform developed for the experiments on interactions between humans and robots, is a robot that has only the upper half of the body and has no locomotion capabilities although it has multiple degrees of freedom and sensor inputs. On the other hand, service robots which are supposed to act in a human living space need to have locomotion capabilities that suit the living space. Robots with locomotion capabilities can act positively to humans or perform practical tasks such as carrying things for them. What kind of locomotion capabilities will be required in the human living space? Human living spaces are fundamentally environments that conveniently suit biped humans although some of the living spaces may be free of barriers for the convenience of assistive devices like a wheeled chair. We, therefore, consider biped walking as a locomotion mode of robots that is most suitable for human living environments.

We have focused our attention on emotional expressions and biped walking capabilities in developing a biped humanoid robot KOBIAN (**Fig. 1**) capable of emotional expressions as a primary prototype in this project. The basic concept of KOBIAN represents an integration of WE-4 and WABIAN-2. Its requirement specifications are as follows:

- Human-like size.
- Biped walking with built-in batteries.
- Visual recognition of environments.
- Emotional expressions.

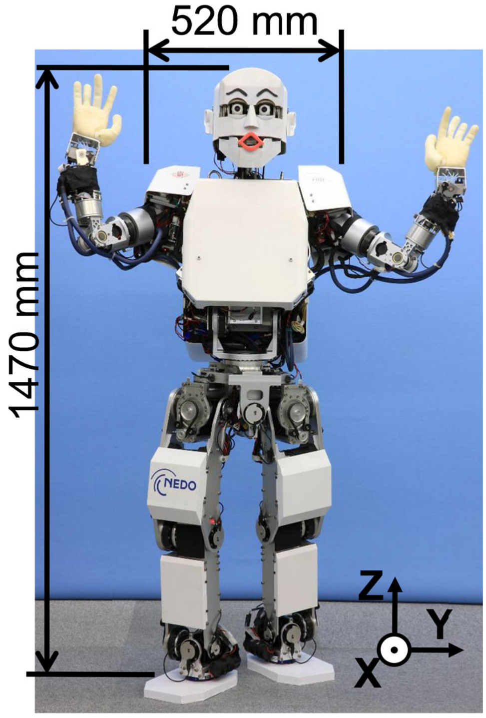

Fig. 1. Picture of KOBIAN.

2.1. System Configuration

In designing biped walking robots, there are several severe constraints to overcome which include weight, size, power system, actuator, control system and so on and these elements need to be successfully organized to achieve biped walking. Since WE-4 is about 20% larger in size than the body of an average male adult and has no capability to walk, we have fully adopted the designs of WABIAN-2 for the entire system configurations of KOBIAN.

All the joints of KOBIAN are to be driven by a DC motor with an encoder activated by an electric motor driver (Tokushu Denso Co., Ltd.), and counter readings of the encoder and output of velocity references to the motor driver are done by the PC embedded in the back of KOBIAN through the I/O boards (HRP interface boards of ZUCO, Co., Ltd.), as shown in **Fig. 2**. 48-DOFs in total that can be controlled with the installed I/O boards are assigned to various parts of KOBIAN as follows: 12 to both legs, two to the waist, one to the trunk, 14 to the both arms, eight to both hands, four to the neck, and seven to the head (**Fig. 3**). These configurations allow biped walking with extended knees in the same way as WABIAN-2.

PC to control the motions of KOBIAN has a CPU of Pentium M 1.8 GHz, a memory of 2 GB, a compact flash memory of 2 GB for storage, three I/O boards and a receiver board for the six-axis force/torque sensors (Nitta) installed in both ankles. OS is QNX Neutrino 6.3.0. Everything can be wirelessly operated through the wireless LAN and remote desktop. A CMOS camera is installed in both eyes to capture images and the environmental recognition is done with a laptop (SONY) which is connected to the control PC in the Ethernet.

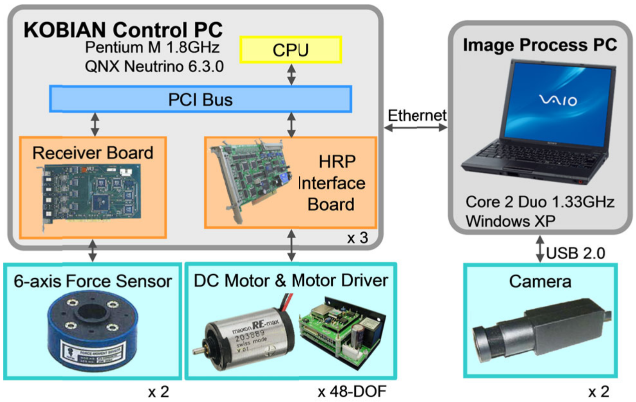

Fig. 2. Control system configuration.

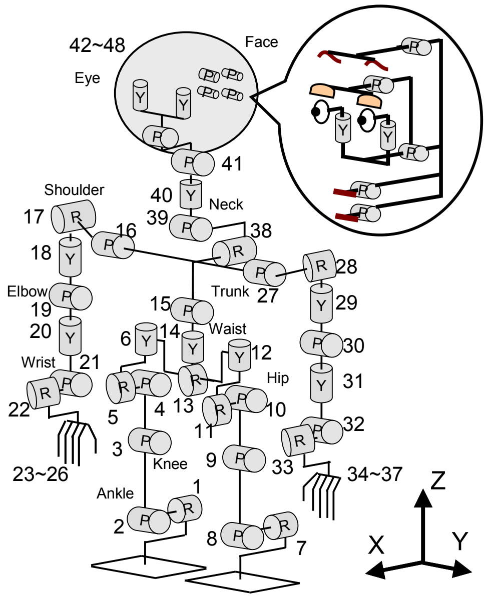

Fig. 3. DOF configuration.

KOBIAN with an embedded lithium-ion battery can make continuous motions for a maximum of 20 minutes without any external power supply. The whole body weighs 62 kg in total.

2.2. Head

Seven-DOFs are assigned to the head according to the number of I/O boards that can be installed. This represents a significant reduction in DOF when compared with WE-4 that had 22-DOFs. WE-4 had a motor and a motor driver installed on the exterior of the head, but with KOBIAN we had to have them embedded in the head that is smaller than that of WE-4. Therefore we have limited the requirement specifications for facial expressions of the primary prototype KOBIAN to the minimum, i.e., happiness and perplexity. This was because we could not expect KOBIAN with the above-mentioned reduction in DOF to make all of the six basic facial expressions, and from the adaptive communication technology point of view (technical area (1) addressed in this project), we have decided that facial expressions to indicate whether robots recognize users' speeches or not (i.e., show happiness when robots recognize speeches or ask back with perplexity when they do not) were necessary particularly in vocal communication.

Table 1. Design requirements of the head.

Category	Specification
Size	■Human-like size
Vision	■Relative position of objects ■Possibility to see its own steps
Emotions	■Perplexity ■Happiness

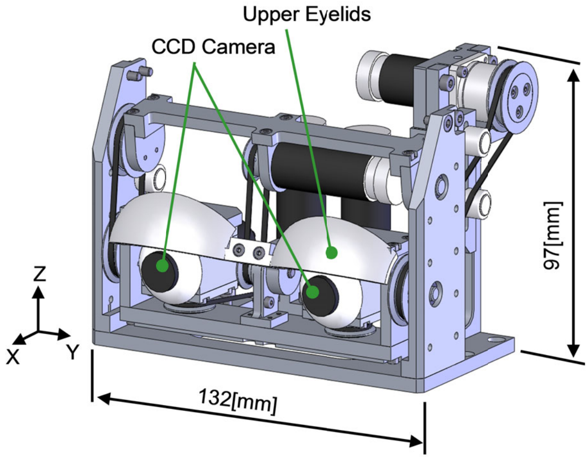

Fig. 4. Mechanical design of eyes.

Requirement specifications for the head are given in **Table 1**. Three-DOFs out of the seven-DOFs assigned to the head are for pitch-axes of the two eyes and yaw-axis of each eye, and the remaining four-DOFs are for the eyebrows, eyelids and mouth for facial expressions. Mechanical designs of the head are described below.

Since eyes are an important part of the head to recognize environments, a CMOS color camera (ARTRAY, ARTCAM-022MINI) with an USB connection is installed in each eye. A total of three-DOFs consisting of 1-DOF for pitch-axes of the two eyes and two-DOFs for yaw-axis of each eye are provided to the eyes to make up for the field of view (60°) of the camera and to deliver intentions by the lines of sight. Mechanical design of the eyes is shown in **Fig. 4**.

KOBIAN has a total of four-DOFs for facial expressions, significantly fewer than WE-4 with 19-DOFs. DOFs for facial motions other than opening and closing of the jaw are all symmetrical. Although requirements for facial expressions are reduced to two, we are not sure if four-DOFs can make adequate facial expressions, in par-

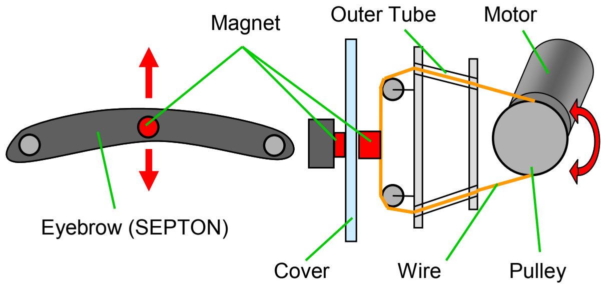

Fig. 5. Mechanism of eyebrow.

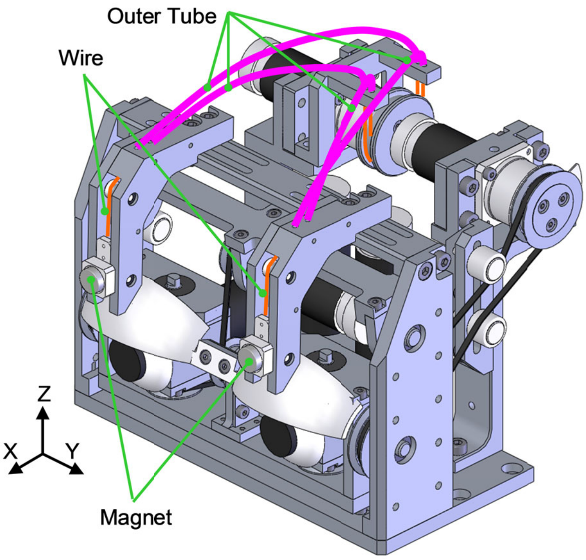

Fig. 6. Mechanical design of eyebrow.

ticular of perplexity that is not included in the facial expressions of WE-4. We have, therefore, designed to represent these emotions by the two axes of positive/negative and arousal/non-arousal; happiness is represented by the positive and non-arousal axis and perplexity by the negative and arousal axis.

WE-4 has four-DOFs for eyebrows that can be changed into various shapes by moving up and down the four control points, KOBIAN's eyebrows have only one control point in the middle and the both ends fixed. KOBIAN with the eyebrows of such construction can make normal and positive facial expressions by low-arch-shape and negative facial expressions by valley-shape. Whereas WE-4 has the control points of the eyebrows directly pulled by a wire with the result of very poor maintainability, KOBIAN has the forehead cover pinched by two magnets outside and inside so that the eyebrows can be driven by the magnet on the inside. Mechanical designs of the eyebrows are shown in **Figs. 5** and **6**.

Whereas WE-4's eyelids have a total of three-DOFs consisting of pitch-axis and roll-axis of the upper eyelid and pitch-axis of the lower eyelid, KOBIAN has only one-DOF for pitch-axis of the upper eyelid so that arousal expressions can be made with the eyelids kept open.

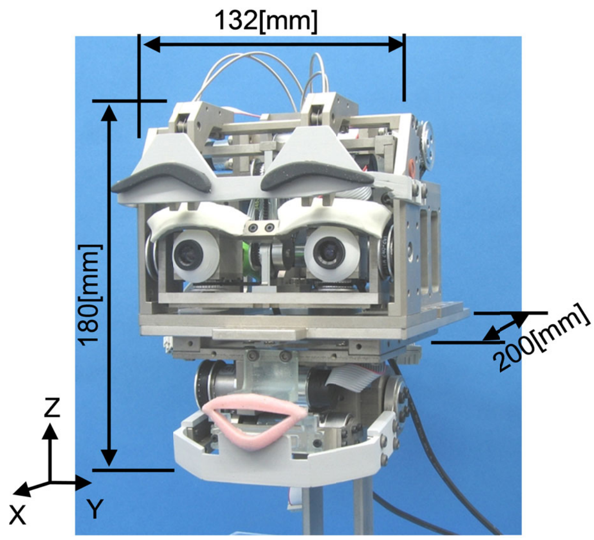

Fig. 7. Inner structure of the head.

WE-4's mouth has 1-DOF for opening and closing of the jaw and two-DOFs at each corner of the mouth with the upper and lower lips fixed to the upper and lower jaws in the middle respectively. KOBIAN has a total of two-DOFs consisting of 1-DOF for opening and closing of the jaw and 1-DOF for moving up and down the both corners of the mouth. Compared with WE-4 that can control the motions of the lips in four ways, that are to close the mouth, to make the shapes of a diamond, normal-triangular and inverted-triangular and also the sizes to the upward/downward and leftward/rightward directions, KOBIAN has a fixed opening size of the mouth in the leftward/rightward direction. In designing KOBIAN, however, priorities have been given to the capabilities to express those four shapes as well as to express robot's speeches together with the movement of the jaws.

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Appearance of the head, which is often used by humans for individual recognition, constitutes an important element in expressing individuality of robots. KOBIAN, therefore, has such designs that mechanism for facial expressions and exterior package can be separated from each other so that various exterior packages can easily be exchanged. Mechanism of the head is shown in **Fig. 7**.

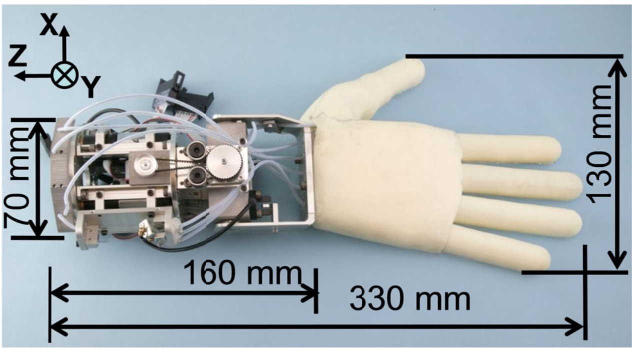


Fig. 8. Overview of WSH-1R.

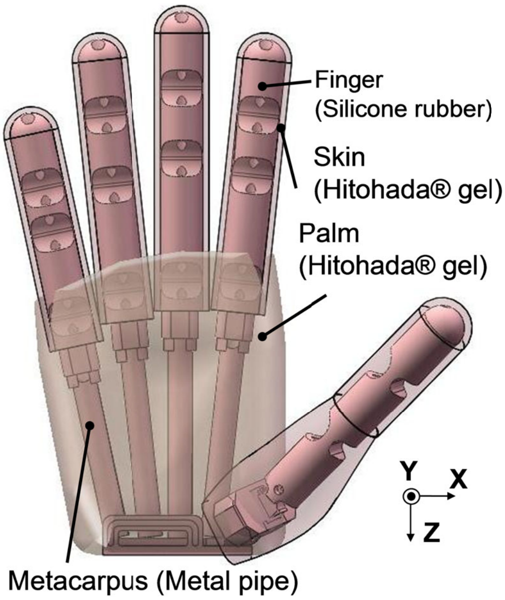


Fig. 9. Structure of the hand.

2.3. Anthropomorphic Soft Hand

We are aiming at developing robots that can support humans in the indoor living environments where in addition to fulfillment of support tasks, safety in contacting humans as well as physical interactions like shake-hands are important elements to be realized.

To meet the above-mentioned developmental objectives, KOBIAN has anthropomorphic soft hands WSH (Waseda Soft Hand) mainly constructed of soft materials (**Fig. 8**) [12–14]. The WSH series was developed with the aim of investigating what kind of tactile impressions the developed hands (softness, shapes, application of forces, etc.) would give in physical interactions with humans.

The WSH series has 4-DOFs per hand, so that it can make simple gestures such as pointing at something and can also hold objects as heavy as 300 g. The palm has a molded structure where inner frames modeled on metacarpal bones are wrapped with a soft material (Hitohada gel of Exseal Co., Ltd.), as shown in **Fig. 9**. Fingers, molded with silicone rubber, can be bended and stretched by means of slits at joints and under-actuated wire (**Fig. 10**).

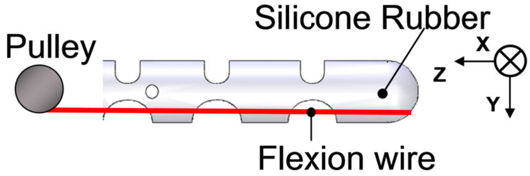


Fig. 10. Drive mechanism of the finger.

3. Experimental Evaluation of the Emotion Expression

We have developed KOBIAN in our judgment that emotional expressions play an important role in human-robot communication. We now describe the experimental evaluations on KOBIAN's performance of such emotional expressions.

3.1. Facial Expression

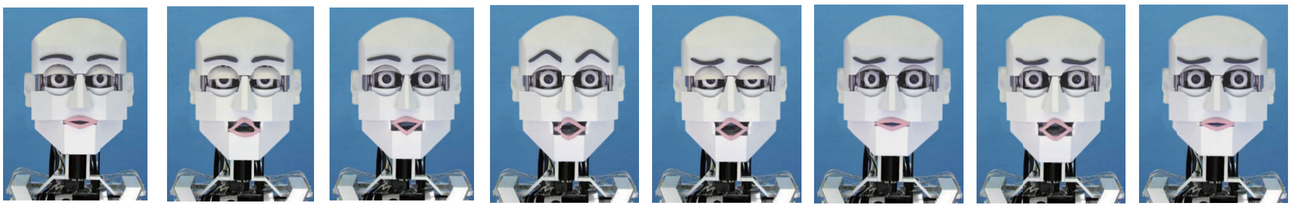
KOBIAN with significantly reduced DOFs for facial expressions than WE-4 is expected to suffer from a drop in performance of facial expressions. Here we evaluate how much that drop is in KOBIAN's performance of facial expressions and whether it is possible for KOBIAN to make facial expressions of happiness and perplexity as designed.

The evaluations are based on a questionnaire survey on the emotion recognition rates as an evaluation index. Emotion recognition rates refer to the percentages of respondents who gave a positive answer to the question whether they find certain facial expressions well representing certain emotions.

A total of 127 young Japanese (average age of 23) have participated in the experiment. The participants were presented with seven photos of WE-4's facial expressions (one of a neutral facial expression and six of the emotional expressions) together with 17 photos of KOBIAN's facial expressions (one of a neutral and 16 of the emotional). The participants were asked to choose what emotion they thought each of the emotional expressions photo expressed from the options of emotions (anger, happiness, surprise, disgust, sadness, fear, perplexity, others). The photos were presented randomly to each of the participants. To exclude any effects by the exterior appearance, we have provided KOBIAN with the similar facial external appearance to WE-4.

KOBIAN's facial expressions that have gained highest recognition rates in the 17 photos are shown in **Fig. 11**. Facial expression recognition rates of WE-4 and KOBIAN for respective emotions are shown in **Fig. 12**.

On the whole, KOBIAN's facial expression recognition rates are lower than those of WE-4, probably due to the reduction in DOF for facial expressions except for disgust and perplexity that have increased. The reason for KOBIAN's facial expression rates for perplexity being higher may be attributed to the fact that WE-4 has no particular facial expressions for perplexity and that KOBIAN has specially assigned DOFs for expressing perplexity.



(a) Neutral (b) Anger (c) Happiness (d) Surprise (e) Disgust (f) Saddness (g) Fear (h) Perplexity

Fig. 11. Facial expressions.

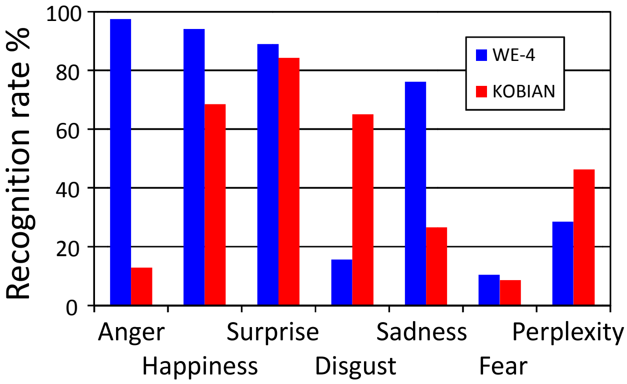


Fig. 12. Results of the facial expression recognition.

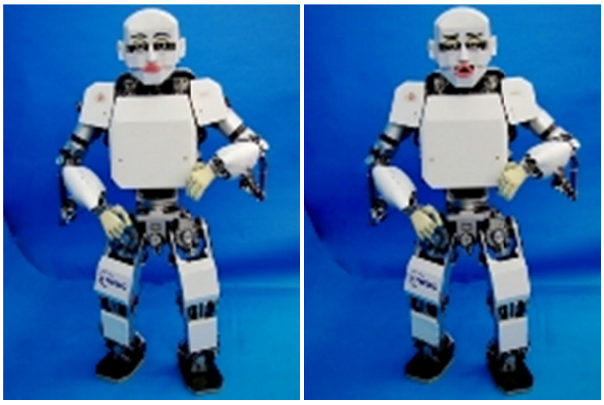
3.2. Whole-Body Emotion Expression

WE-4RII [15] is a humanoid robot that can express emotions using not just the head as in WE-4 but also arms and upper half of the body. In comparison to WE-4RII, KOBIAN has lower limbs and can perform more dynamic expressions using the whole body.

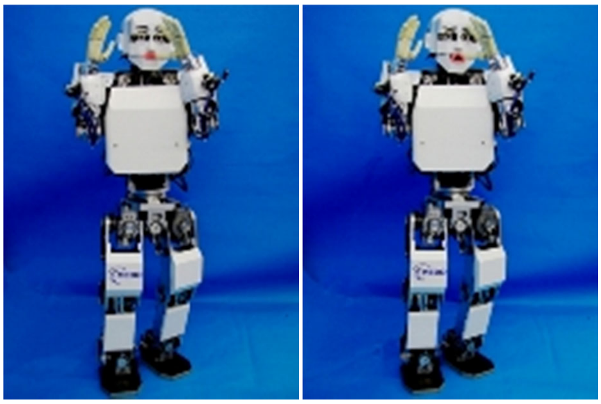
Here we evaluate KOBIAN's performance for emotional expressions using the whole body. First, we let KOBIAN take postures to express emotions using the whole body. Next we took photos of emotional expressions with facial expressions only, with body expressions only, and with facial plus body expressions. Using these photos we have conducted the same questionnaire survey as in Section 3.1 for emotional expression recognition rates. A total of 30 young Japanese (average age of 26) have participated in the experiments. Some examples of the whole-body emotional expressions are shown in **Fig. 13** and emotional expression recognition rates by facial expressions, by body expressions and by facial plus body expressions, are in **Fig. 14**.

The survey findings show that the average emotional expression rate by facial expressions only is 44.6% and 33.8% by body expressions only. The average emotional expression rate by facial plus body expressions have significantly gone up to 70.0%. On the whole, emotional expression recognition rates by a combination of facial and body expressions are higher than those by facial expressions only or by body expressions only; combined use of facial and body expressions prove effective for emotional expressions of robots.

As for emotional expression recognition rates for happiness and disgust, facial expressions only provided better rates than a combination of facial and body expressions. We have therefore decided to further improve the KOBIAN's postures to express emotions using the whole body.



(a) Anger (body) (b) Anger (facial + body)



(c) Fear (body) (d) Fear (facial + body)

Fig. 13. Examples of the pictures.

Since the KOBIAN's postures used in the above-mentioned experiments for emotional expressions by body were worked out by the experimenters, we have decided to request a photographer and a comic artist, both with professional abilities in expressions, to render postures for emotional expressions this time. Using the photos of the emotional expressions by whole body as worked out by them (three to four patterns per emotion), we have conducted a similar questionnaire survey for emotional expression recognition rates with 33 young Japanese (av-

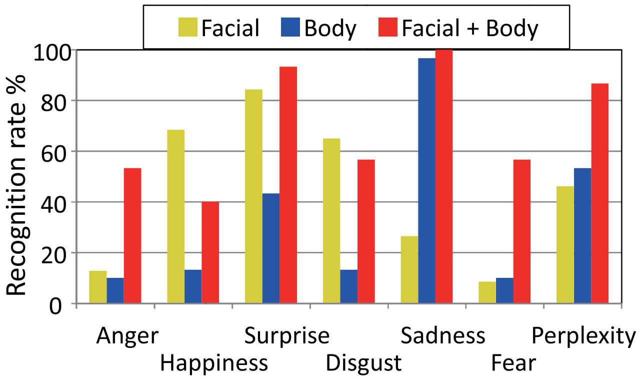


Fig. 14. Comparison of facial and body expressions.

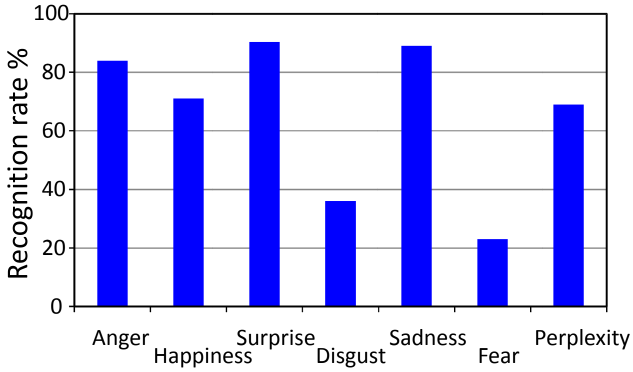
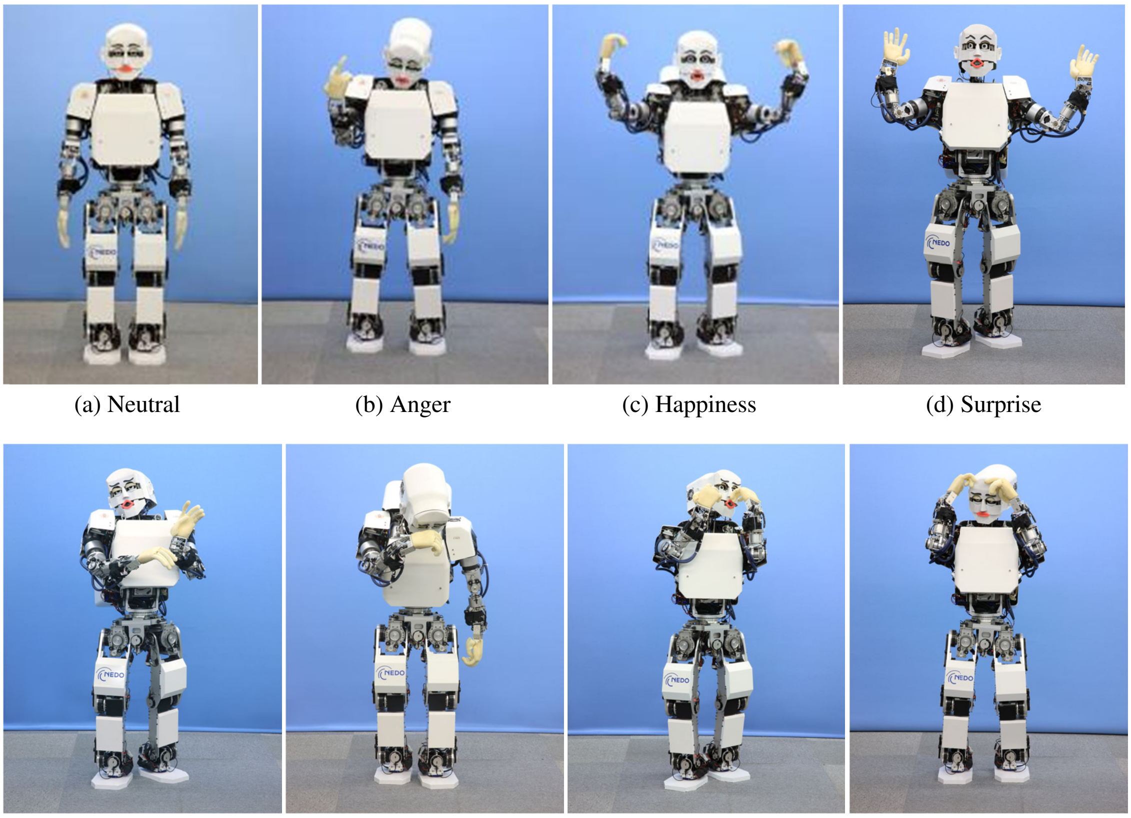


Fig. 15. Results of the whole-body emotion expression recognition.



(a) Neutral (b) Anger (c) Happiness (d) Surprise

(e) Disgust (f) Sadness (g) Fear (h) Perplexity

Fig. 16. Whole-body emotion expressions.

erage age of 27). **Fig. 15** shows the whole-body emotional expression recognition rates for respective emotions and **Fig. 16**, the photos of emotional expressions that have gained the highest recognition rates.

4. Conclusion

In today's rapidly aging society with fewer children and declining workforce in Japan, Robot-Technology (RT)-based devices or services are expected more than ever to play an important role in the human living space in order to realize a lifestyle that is much safer, more secure, more convenient and more comfortable than now. Such social demands are bound to create and flourish robotic service industries to support the daily living activities of elderly people in future.

For such service robots to meet the above-mentioned social demands, we have proposed biped humanoid robots and were commissioned by NEDO to do a research on the "Development of RT-Based Systems to Support Comfortable Lifestyle" as a part of the NEDO's Strategic

Advanced Robotics Element Technology Development Project – Area of Service Robots – RT-Based Communication Systems with Elderly People for the period between 2006 and 2009. As a result, we have developed biped humanoid robot KOBIAN capable of whole-body emotional expressions.

KOBIAN, developed on the basic concept of integration of WE-4 and WABIAN-2, has not only functions for emotional expressions and environmental recognition but also biped walking capabilities. KOBIAN's head has fewer DOFs for emotional expressions than WE-4. It has anthropomorphic soft robot hands WSH made of soft materials for physical interactions with humans.

We have evaluated KOBIAN's basic performance of emotional expressions on the belief that emotional expressions constitute an important and useful element in human-robot communication. The evaluations show that KOBIAN performs poorer than WE-4 in the recognition rates of emotional expressions by facial expressions only but KOBIAN's emotional expressions by a combination of facial and body expressions have better recognition rates than WE-4 for some particular emotions.

KOBIAN's head is only allowed limited DOFs because of its control system structure (motor control with I/O boards). We intend to review the control system structure further as we believe a much smaller and more multichannel control system would allow more DOFs to be assigned to the head.

KOBIAN has only visual sensors for sensational input, which leads to a narrower range of communication between humans and robots. KOBIAN should also have auditory and tactile sense devices as WE-4 does. As for emotional expression performance evaluated with still photos in this paper, we intend to evaluate the performance for emotional expressions in combination with vocal expressions as well as dynamic emotional expressions in the execution of tasks or in interactions between humans and robots in the future.

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