A Face Robot Actuated With Artificial Muscle Based on Dielectric Elastomer

Jong Won Kwak, Ho June Chi, Kwang Mok Jung, Ja Choon Koo
School of Mechanical Engineering, Sungkyunkwan University, Chunchun-dong, 300, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea
Jae Wook Jeon
School of Information and Communication Engineering, Chunchun-dong, 300, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea
Youngkwan Lee, Jae-do Nam
School of Applied Chemistry, Sungkyunkwan University, Chunchun-dong, 300, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea
Youngsun Ryew
Robolands Co., Hnyang Business Incubator, 1271 Sal-dong, Sangrok-gu, Ansan-si, Kyunggi-do 426-791, Korea
Hyouk Ryeol Choi*
School of Mechanical Engineering, Sungkyunkwan University, Chunchun-dong, 300, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea

Face robots capable of expressing their emotional status, can be adopted as an efficient tool for friendly communication between the human and the machine. In this paper, we present a face robot actuated with artificial muscle based on dielectric elastomer. By exploiting the properties of dielectric elastomer, it is possible to actuate the covering skin, eyes as well as provide human-like expressivity without employing complicated mechanisms. The robot is driven by seven actuator modules such eye, eyebrow, eyelid, brow, cheek, jaw and neck module corresponding to movements of facial muscles. Although they are only part of the whole set of facial motions, our approach is sufficient to generate six fundamental facial expressions such as surprise, fear, angry, disgust, sadness, and happiness. In the robot, each module communicates with the others via CAN communication protocol and according to the desired emotional expressions, the facial motions are generated by combining the motions of each actuator module. A prototype of the robot has been developed and several experiments have been conducted to validate its feasibility.

Key Words : Face Robot, Head Robot, EAP, Artificial Muscle, Dielectric Elastomer

1. Introduction

Recent development of robot technologies realizes even the robot like human beings while generating friendly interaction with them. To make the robot more intimate to the human, it is prerequisite to have a tool for executing verbal communications, exchanging intentions and emotions. According to the studies on psychology, however, they say that facial expressions with the face robot are crucial for friendly communication with the human beings.

* Corresponding Author,
E-mail : hrchoi@me.skku.ac.kr
TEL : +82-31-290-7449; **FAX** : +82-31-290-7507
School of Mechanical Engineering, Sungkyunkwan University, Chunchun-dong, 300, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea. (Manuscript **Received** July 2, 2004; **Revised** December 10, 2004)

Issues of the face robot are addressed as three ; aesthetic design, mechanism for actuation, emotional expressivity or intelligent interaction. In the aesthetic design, there exist two extremes between realism (Kobayashi et al., 2002) and caricatures (Breazeal and Scassellati, 1999), but it should be noted that the perfect copy of the human face may arise negative impression of the robot rather than the intimacy. In the issue of intelligent interaction, it has been addressed that several determined patterns of movements can transfer the emotional expressions (Miwa et al., 2001). Up to now, there have been several approaches as the actuating means of the face robot such as pneumatic cylinder (Kobayashi and Hara, 1993), Shape Memory Alloy (SMA) actuator (Kobayashi et al., 1999), McKibben pneumatic muscle (Kobayashi et al., 2001 : Ahn and Tanh, 2004), motors (Miwa et al., 2001 ; Edsinger et al., 2000), artificial muscle based on ElectroActive Polymer (EAP) (Hanson et al., 2001). However, the existing technologies available to the robotic researchers constrain the range of viable design of the face robot.

Polymers are recently getting more attention as new energy transformers in many different application fields mainly thanks to their lighter weight and higher efficiency compared to traditional electromagnetic transducers. Although several polymeric energy transforming materials are available for current transducer researches, ElectroActive Polymers (EAP) appear to have great potential to be a new alternative actuator (Yoseph, 2004). Various EAPs including Ionic Polymer Metal Composite (IPMC), Conducting Polymer (CP), polymer gels, dielectric elastomer, and piezoelectric polymer are adopted for new kinds of transducer constructions. In spite of the technical difficulties their application areas are rapidly expanding by many researchers, especially in robotic fields since actuation mechanism of the polymers is similar to human muscle. Among them, the dielectric elastomer has several advantageous features over the others on the point of large strain, high force-to-weight ratio, dry actuation regardless of high driving voltage input, which has been proven to possess high potential of mimicking or replacing the human muscles recently (Choi et al., 2003 ; Pelrine et al., 1998).

In an attempt to exploit these properties, we have developed a face robot capable of replicating human facial expressions. By using the properties of dielectric elastomer, it is possible to actuate the covering skin as well as provide human-like expressivity without employing complicated mechanisms. The robot is driven by seven actuator modules such as eye, eyebrow, eyelid, brow, cheek, jaw and neck module corresponding to Action Units of Facial Action Coding System by Ekman (1977). Although they are only part of the whole set of Action Units (AUs), our approach is sufficient to generate six fundamental facial expressions such as surprise, fear, angry, disgust, sadness, and happiness. In the robot, each module communicates with the others via CAN communication protocol and according to the desired emotional expressions, the facial motions are generated by combining the motions of each actuator module.

Succeeding sections of the paper are organized as follows. First, actuation points on the face are determined. Next, basic operation mechanism of the dielectric elastomer is addressed and then, generic designs of the actuator modules are presented with the description of the system construction. Finally, the prototype of the face robot is introduced and experimental results are added.

2. Determination of Actuation Points

Among the previous researches on physiology, Ekman developed FACS (Facial Action Coding System) based on the movements of facial muscles (Ekman and Friesen, 1977). He classified facial motions into 46 distinct groups and analyzed the facial expressions such as surprise, fear, angry, disgust, sadness, and happiness according to the combination of AUs. By employing this method, Kobayashi and Hara determined the actuation patterns of the face robot. To express six basic facial motions, 12 AUs among 46 ones has been selected as listed in Table 1. 18 control points

Table 1 AUs for expressing six basic facial motions

AU Number	FACS Name
1	Inner Brow Raiser
2	Outer Brow Raiser
4	Brow Lowerer
5	Upper Lid Raiser
6	Cheek Raiser
7	Lid Tightener
9	Nose Wrinkler
10	Upper Lid Raiser
12	Lip Corner Puller
15	Lip Corner Depressor
17	Chin Raiser
20	Lip Stretcher
25	Lips Part
26	Jaw Drop

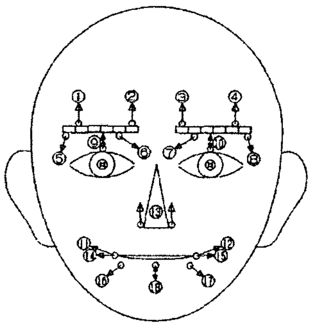


Fig. 1 Control points

have been experimentally determined as shown in Fig. 1, and consequently, they are selected as the actuation points on the face robot (Kobayashi and Hara, 1993).

In order to map the human facial expression onto those of the robot, preliminary experiments were conducted in this research. The points for monitoring the movements were chosen such as eyebrow, eyelid, forehead, lip, cheek and markers were attached for capturing the motions. The marker located between the eye and the tip of the nose is the reference point for the analysis. Figure 2 represents the six basic facial expressions, that is, surprise, fear, angry, disgust, sad-

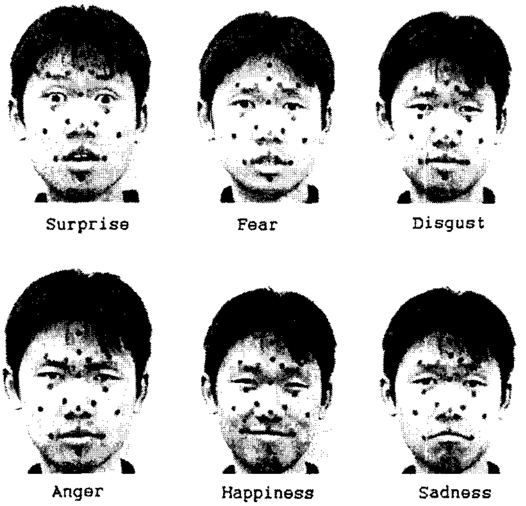


Fig. 2 Six basic facial expressions with marker attachment

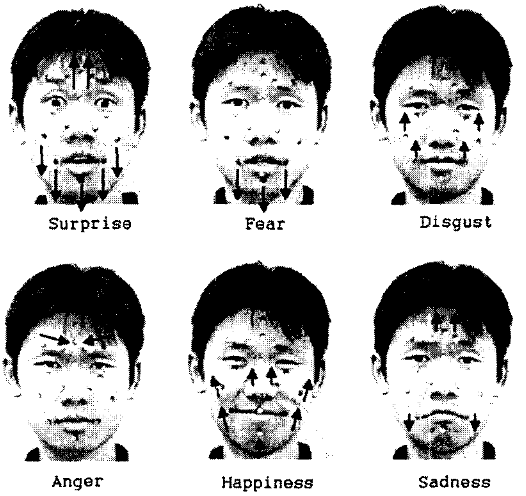


Fig. 3 Comparison of marker attachment

ness, and happiness. The relative motions of the face were detected by comparing the positions of markers when the subject made a facial expression as shown in Fig. 3. For instance, "surprise" accompanies the motions that the eyebrow moves up, wrinkles appears on the forehead, eyes are enlarged, and the jaw is open. In the case of "fear" the eyebrow moves up, the mouth is open and the lips are pulled horizontally. By summarizing the results of preliminary experiments the

Table 2 Six basic facial expressions and AUs used

Expression	AUs
Surprise	1, 2, 5, 15, 26
Fear	1, 2, 20, 25
Disgust	4, 6, 10
Anger	2, 7
Happiness	6, 9, 17
Sadness	1, 15

change of facial expressions were incorporated to AUs correspondingly as listed in Table 2. Consequently, forehead, eyebrow, eyelid, cheek, and mouth have been selected as the principal points of actuation based on the results of preliminary experiments. In fact, the data above entirely depends on static movements of the face but dynamic motions are required to generate more realistic expressions. For example, the motion of the neck has effect on the surprise and the direction of gaze influences the overall emotional expressions. Thus, we try to use not only the motions of the face, but mimic the change of gaze and that of the neck for realistic expression of emotions in this work.

3. System Overview

As shown in Figs. 4, 5 and 6, the face robot consists of seven actuator modules that is, eye, eyebrow, eyelid, cheek, brow, jaw and neck module with a skull which plays as a skeletal structure. All the modules except the jaw and the neck are actuated by the artificial muscle actuators proposed. Motors are utilized on the control point requiring relatively large forces. For example the jaw is driven by an RC-servo motor and the neck is actuated by three DC servo motors. The face of the robot is covered with an off-the-shelf plastic mask without paying any special treatment. Each module possesses an embedded controller (PIC18F258/458) which can control the actuation and communicate with the others via CAN protocol. Thus, removal/insertion of additional modules are easy and control points can be multiplied as well. Also, since all the actuators with driving and control circuits are embedded in the robot, compactness in size is achieved without problems in wiring, even although its total degree-of- freedom (DOF) goes up to 24 as listed in Table 3.

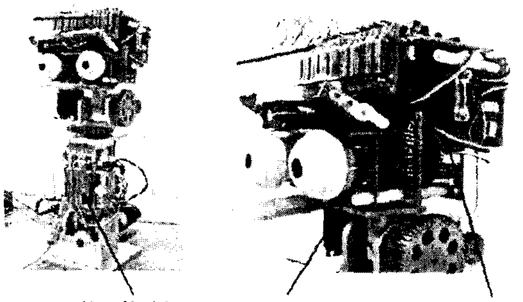


Fig. 5 Photo of face robot without covering

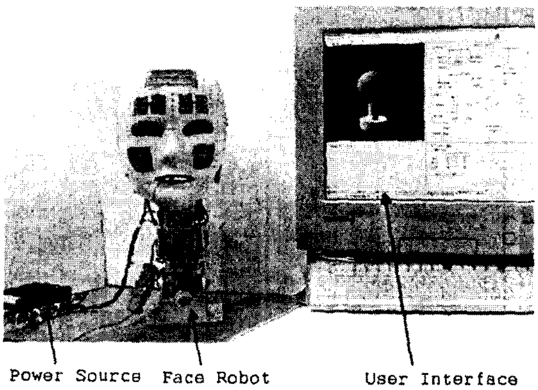


Fig. 4 Photo of face robot

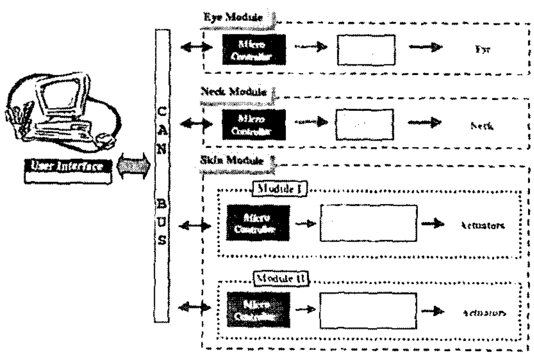


Fig. 6 System layout of face robot

Table 3 DOF of modules in face robot

module	dof	number of module	subtotal
neck	3	1	3
jaw	1	1	1
eye	5	2	10
eyebrow	2	2	4
Eyelid	1	2	2
Cheek	1	2	2
Forehead	2	1	2
Total			24

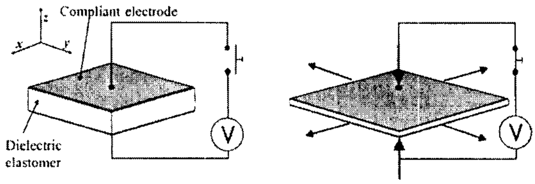


Fig. 7 Basic operation in transduction

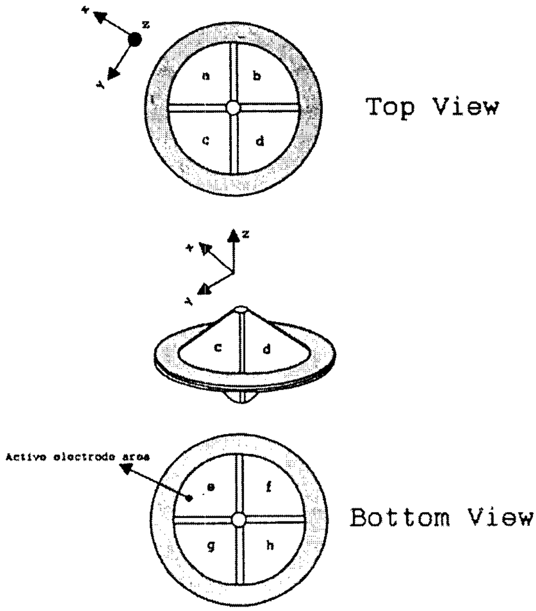


Fig. 8 Design of multi-DOF actuator

4. Description of Actuator Modules

4.1 Basic principle of actuation

The actuator developed here is fabricated with dielectric elastomer. The physics of actuation is elaborated and well documented in some publications (Pelrine et al., 1998). The principle of operation is based on the electromechanical transduction of a parallel two-plate-capacitor. A schematic overview of the basic actuation mechanism is shown in Fig. 7.

When a voltage potential is applied across the dielectric elastomer film coated with compliant electrodes on both sides, the material is compressed in thickness and expands in lateral direction. By virtue of this contraction caused by the charged electrical energy across the thickness of the material, mechanical actuation force is generated. This physics clearly links mechanical and electrical energy domain where energy transduction happens. The effective mechanical pressure along the thickness direction by electrical input is given by,

$$\sigma_e = -\varepsilon_0 \varepsilon_r E^2 \tag{1}$$

where E is an applied electric field, ε_0 and ε_r are electric permittivity of free space and relative permittivity respectively. Mechanical actuation could be acquired through either the effective pressure caused axial contraction or lateral expansion of the dielectric elastomer block. According to the previous researches, the bandwidth of the actuator is estimated around 200 Hz, and its actuation speed may go up to 1 kHz in maximum (Yoseph, 2004).

4.2 Eye module

The actuation of the eye module is based on the multi-DOF actuator proposed by the authors as illustrated in Fig. 8 (Choi et al., 2003). The actuator consists of eight polymer film sections, four sections on each side. It can be manufactured by simply partitioning the elastomer surface and applying the carbon coating separately on each partitioned area during electrode coating process. Since each polymer section is to be packaged separately, each quadrant must be controlled independently. A proper combination of individual motions of each section might provide continuous multi-DOF actuation. For example, when sections d and h are actuated, the output

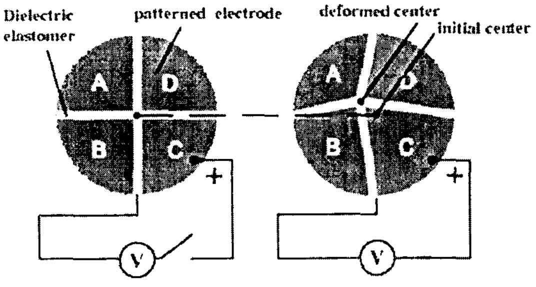


Fig. 9 Translational motion of multi-DOF actuator

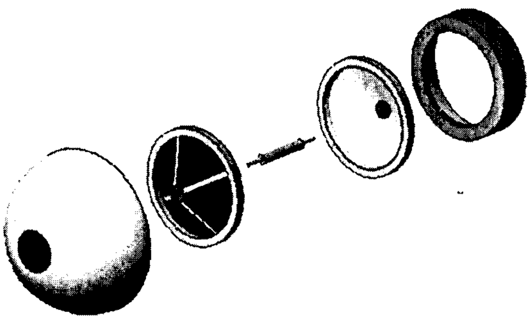


Fig. 10 Exploded view of eye module

terminal moves to positive x direction. Figure 9 shows a generic idea for creating translational motions. If sections c and f are turned on in non symmetric input pattern, the output terminal will be tilt with respect to positive x axis. Then if the control action succeeds to provide electrical input to sections d and e, the terminal will rotate about positive y axis. The further continuous control action with proper adjustment of input voltage during the transition of the rotation axis enables to keep the terminal in smooth rotation. The eyeball is attached at the output terminal of the actuator as depicted in Fig. 10 and thus five DOF motions are generated. In this work, we have not attached the camera unit at the eyeball, which can be conducted as the future work.

As shown in the overall schematic of the eye module depicted in Fig. 11, we use a microcontroller (PIC18F258 by Microchip) including the CAN module, which manages the control, communication via CAN and DAC (Digital to Analog Converter). DAC (TLV5614 by Texas Instrument) converts the digital inputs from the microcontroller to the analog ones for the actua-

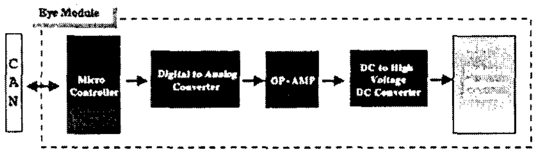


Fig. 11 Layout of eye module

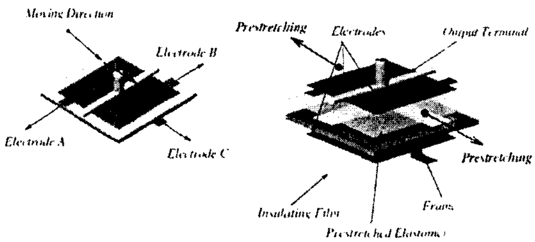
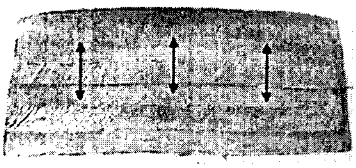


Fig. 12 Operational principle of ANTLA

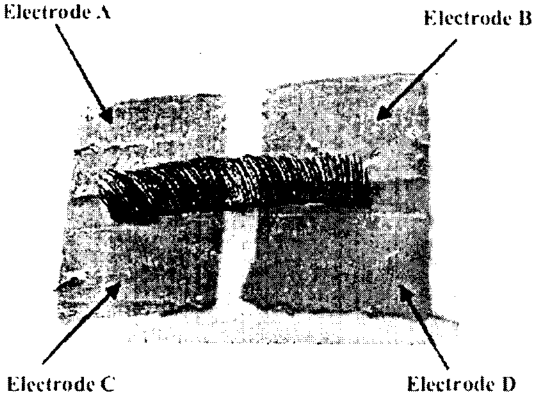
tor unit and operational amplifier (TLV 4112 by Texas Instrument) multiplies the currents of the inputs. In the final stage of the driving circuit, a high voltage DC-DC converter (Q30-5 by EMCO) generates the driving voltage to the dielectric elastomer.

4.3 Skin module

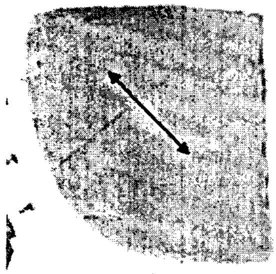
Since three modules such as eyebrow, cheek, brow module are driven by the configuration of the actuator shared by each other, they are called the skin module in the work. The operation of modules are based on the actuating principle named as ANTLA (ANTagonistically-driven Linear Actuator), proposed by the authors as conceptually illustrated in Fig. 12 (Choi et al., 2003). In the proposed design, the actuator is mainly composed of a pre-stretched elastomer film foiled on the frame, which is engaged with uniform pretension along the actuation direction. Compliant electrodes are coated on both sides of the elastomer film. Also, a mechanical output terminal is attached on the borderline of partitioned electrodes that is, electrodes A and B on the upper surface, and the common electrode C coated on the bottom. Though it is fabricated with a single elastomer film, it can act like two actuators configured antagonistically and thus, it makes bidirectional actuation possible in "push-pull type" motion. Its working principle is simply



(a) Forehead



(b) Eyebrow



(c) Cheek

Fig. 13 Skin actuator

described as follows. Assuming that uniform pretensions are engaged, tensions on both sides of the elastomer film are initially balanced along the moving direction. When either side of the elastomer is actuated, the actuated part expands, and the force equilibrium is broken accordingly. The output terminal, therefore, moves by the difference of elastic restoring force between both sides of the elastomer. For example, if a positive input voltage is given on the electrode A, a negative one on B, and a negative one on C, then the output terminal moves toward the electrode B because the elastomer on the electrode A expands due to the input voltage on A. Also, if a positive voltage is given on the electrode B, a

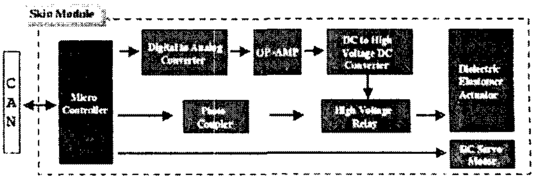


Fig. 14 System layout of skin module

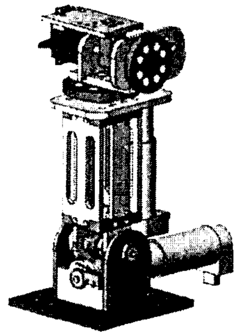
negative one on A, and a negative one on C, then the output terminal moves toward the electrode A. This is the fundamental features of the actuator, that is forward and backward motion, which is possessed by all the existing actuators. However, the proposed actuator can accomplish additional features hard to realize in the existing actuators. The compliance of the actuator can be actively modulated by controlling input voltages. For instance, if positive input voltages are given on electrodes A and B simultaneously while keeping the negative voltage on C, the output terminal is able to be converted to a highly compliant state. Also, it becomes highly stiff when all the voltages are the same. Accordingly, the proposed actuator achieves four typical states of human muscles, that is forward, backward, highly compliant and highly stiff. Figure 13 represents three modifications of ANTLA for forehead, eyebrow, cheek, respectively. In the case of forehead, two strips of actuators are adopted and two ANTLAs' are utilized for generating tilting motion of the eyebrow module. As shown in Fig. 14 a microcontroller (PIC18F458 by Microchip) is adopted for each module and high voltage relays are utilized in the skin module because multiple actuators have to be controlled with single power source.

4.4 Neck module

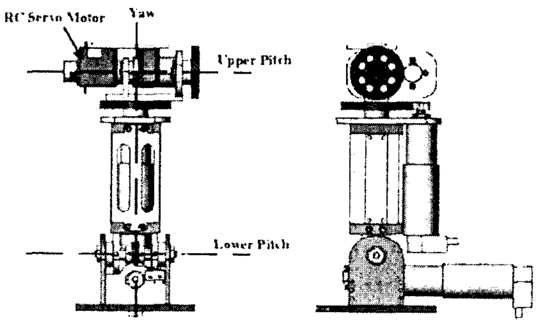
3-DOF neck module, since it requires large forces, is actuated with three DC motors as illustrated in Fig. 15. It has two DOFs for pitching motion and one for yawing. Although limited motions compared to those of the human can be realized, two-DOF gazing motion is provided using pitching. Shaking motion of the head is possible using yawing. The driving system for operating three DC servo motors (Maxon) and a dedicated motor controller have been developed to ensure embedding of all the circuit as shown in Fig. 16. The motor controller, which contains a microcontroller (PIC18F258), a motor driver chip (LMD18200) manages CAN, trajectory generation, and PID control.

4.5 Jaw and eyelid module

The actuation of the jaw and eyelid modules are accomplished with RC servo motors. PWM (Pulse Width Modulation) signal is generated using the timer of the microcontroller, and the positions of RC servo motors are controlled by the signal.



(a) Perspective view



(b) Front/side view

Fig. 15 Illustrated neck mechanism

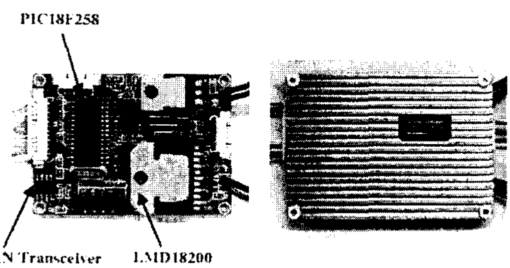


Fig. 16 Motor controller for neck mechanism

5. Experimental Evaluations

The proposed robot has been experimentally validated. In the experiments, each actuator modules were tested and preliminary experiments on the emotional expressions were performed using the face robot developed.

5.1 User interface

For the operation of the face robot, a user interface depicted in Fig. 17 was built. The user interface is largely composed of two windows, one of them is for the graphic display of the robot (designated as section 1 in Fig. 17) and the other is allowed for the commands to the robot (from section 2 to 8 in Fig. 17). The window for command not only gives commands to the individual actuators, but the emotional commands such as happiness, surprise etc.

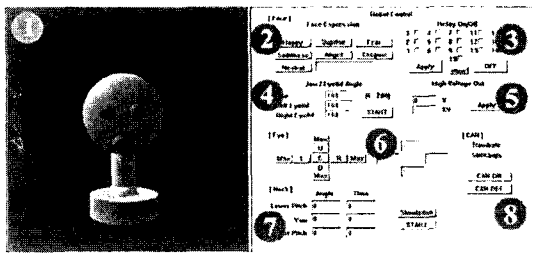


Fig. 17 User interface

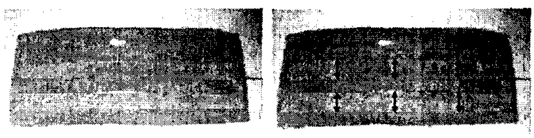


Fig. 18 Movement of forehead

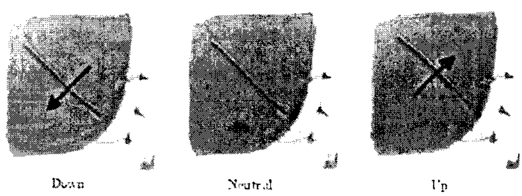


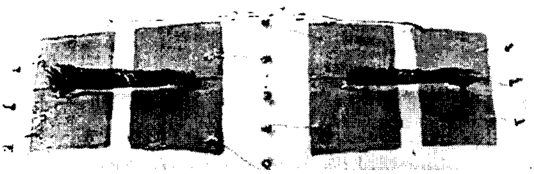
Fig. 19 Movement of cheek

5.2 Actuation tests for individual modules

In advance, the actuation of seven actuator modules have been tested. Figure 18 shows the motion of the forehead module. Two adjacent ANTLAs mimick the wrinkle in the forehead and the motion of cheeks could be generated similarly as shown in Fig. 19. Also, as shown in Fig. 20, asymmetric actuation of two parallel ANTLA realizes tilting motion of the eyebrow that is a quite important accent in the emotional expressions. The movements of eyes are shown in Fig. 21, typically up/down/left/right. Figures 22, 23 and 24 demonstrate the motions of eyelid, jaw, and neck module.

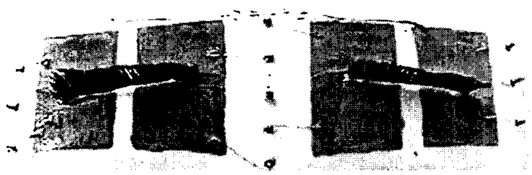
5.3 Expression of emotional status

The emotional commands to the robot could be generated using the software interface developed by the authors as shown in Fig. 17. In advance, the AUs corresponding to each emotional expression were determined as shown in Table 4. Also, the motion of the eye and neck were added to increase the reality of expression, which was quite helpful to discriminate the facial expressions clearly. Figure 25 displays the experimental results for the six emotional expressions. The incorporated motions of AUs give six different emotional feelings successfully. It can be confirmed that the proposed actuation method is



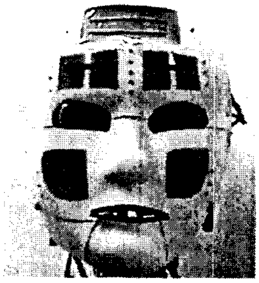
(a) Neutral position

(b) Tilt up

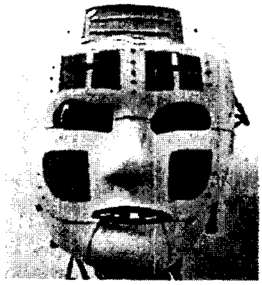


(c) Tilt down

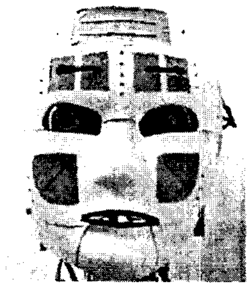
Fig. 20 Movement of eyebrow



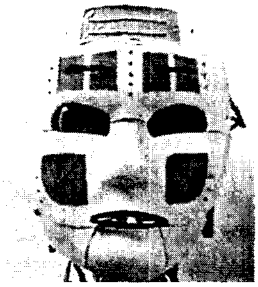
(a) Up



(b) Down



(c) Left



(d) Right

Fig. 21 Movement of eye

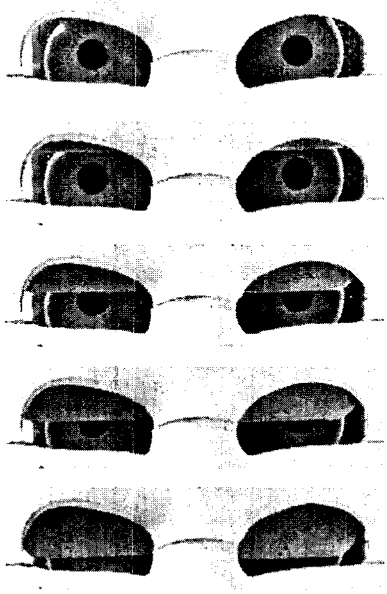


Fig. 22 Movement of eyelid

Table 4 AUs defined for emotional expressions and movements of eye and neck

Expression	AUs	Eyes and neck motion
Surprise	1, 2, 5, 26	Eye up
Fear	1, 2, 5	–
Disgust	4, 6, 41, 17	–
Anger	2, 17	Neck Down
Happiness	6, 26	–
Sadness	1, 24, 41	Eyes Down

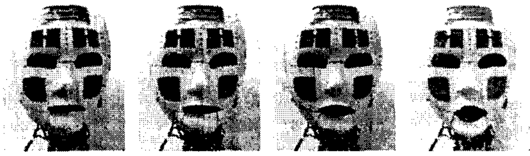


Fig. 23 Movement of jaw

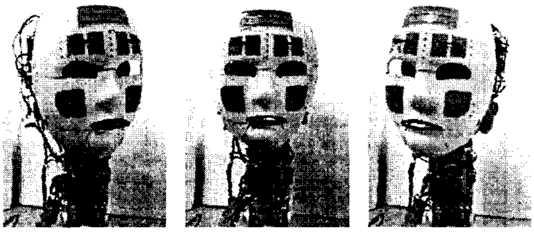
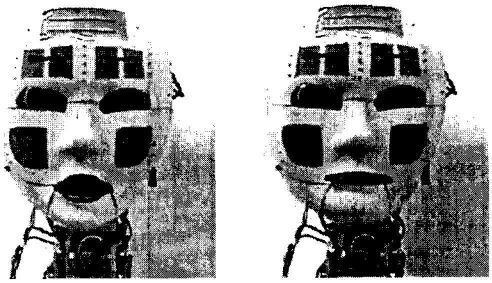
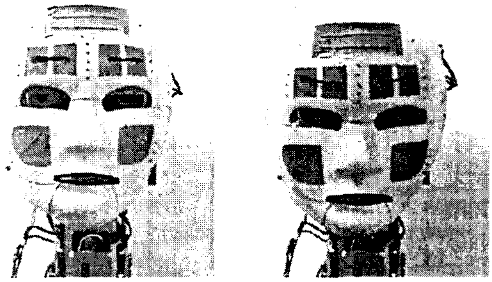


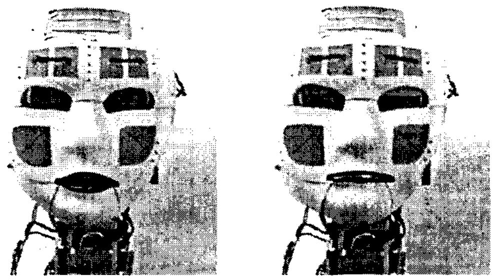
Fig. 24 Movement of neck



(a) Surprise (b) Fear



(c) Disgust (d) Anger



(e) Happiness (f) Sadness

Fig. 25 Six emotional expressions of face robot

effective for the face robot, though the psycho-physical test with the human subjects is required as a further research.

6. Conclusions

Recently most of robotic researchers address that the face robot as the gateway of emotional interaction between the human and the robot. On the contrary, the viable realization of the requirement are limited by technologies available currently, especially the actuating means because a lot of actuators should be integrated within a small space and generate dexterous motions to provide natural emotional expressions of the face robot. In this work, we proved that the actuator based on artificial muscle made of dielectric elastomer could be a prospective candidate for the actuator, and its effectiveness has been demonstrated with a prototype of a face robot. The characteristic features over the previous face robots in the proposed method are summarized as 1) the embedded actuation and 2) multiple DOF actuations without complicated mechanism. The proposed actuation method can be used as a promising means of actuation for the face robot as well as the other domains of actuation such as hands, arms in the future.

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