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FACIAL DESIGN FOR HUMANOID RODOT

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Abstract. *In this research, the authors succeeded in creating facial expressions made with the minimum necessary elements for recognizing a face. The elements are two eyes and a mouth made using precise circles, which are transformed to make facial expressions geometrically, through rotation and vertically scaling transformation. The facial expression patterns made by the geometric elements and transformations were composed employing three dimensions of visual information that had been suggested by many previous researches, slantedness of the mouth, openness of the face, and slantedness of the eyes. In addition, the relationships between the affective meanings of the visual information also corresponded to the results of the previous researches. The authors found that facial expressions can be classified into 10 emotions: happy, angry, sad, disgust, fear, surprised, angry*, fear*, neutral (pleasant) indicating positive emotion, and neutral (unpleasant) indicating negative emotion. These emotions were portrayed by different geometric transformations. Furthermore, the authors discovered the "Tetrahedral model", which can express most clearly the geometric relationships between facial expressions. In this model, each side connecting the face is an axis that controlled the rotational and vertically scaling transformations of the eyes and mouth.*
Keywords: Facial expression, Emotion, Design, Human factors

1. **Introduction.** When human beings communicate with each other, their faces convey the most important and richest information, and their facial expressions are by far the most essential element for understanding the other's emotion. Various elements such as the eyes, mouth, and nose are contained in the face, and these are transformed to form facial expressions. Transformation is the method we use to make expressions.

For many primates including human beings, the eyes are one of the most important factors used to recognize a face as a face [1-3]. In addition, visual preference for face figures (patterns in which three figures are arranged at the top of an upside-down triangle) [4,5] and research on perceptions of upside-down faces [6,7] are well known regarding facial recognition. These research results have suggested that primates recognize faces as sets of configural information comprised of facial elements, and in particular, the eyes and the mouth are the most important elements of all.

Meanwhile, these days there are two theories regarding the recognition of facial expressions: the "category perception theory" and the "dimension theory" [8-10].

The category perception theory states that human beings judge the meaning of facial expressions through 7±2 universal categories common to all human beings. This theory is based on a basic theory of cognition and emotion [12] stemming from evolutionary theory [4]. Those who advocate this theory insist that facial expression is not a continuous variate but a discrete variate, and deny the presence of the psychological dimension described later in the cognitive process of expression [10]. In terms of emotional categories, the six basic emotions (happy, angry, sad, disgust, fear and surprise) advocated by Ekman and many other researchers are the most typical. Basic emotions synchronize with physiological responses and signals to the body such as facial expressions [14], and it is proposed that facial expressions can be classified under one of the six basic emotions without exception irrespective of culture [15-21].

The dimension theory proposes that affective category judgment is conducted following previous judgment that the facial expression is located as one point in two or three dimensional space [8,10], and that facial expression is a continuous variate. In addition, those who advocate this theory insist that the universal factor for human beings is not category but dimension [13]. Dimension theory begins with Schlosberg's theory of the dimension of emotion, for example the circular ring model [22] comprising two dimensions, namely pleasant vs. unpleasant and attention vs. rejection, and the circular cone model [23] comprising the previous two dimensions plus tension vs. sleep [8,10,24]. Since this research, many researchers have discussed such affective meaning dimensions and have repeatedly encountered three dimensions: the pleasantness dimension (pleasant vs. unpleasant), the attention vs. rejection dimension, and the activeness (awareness) dimension (aware vs. asleep) [8-10,24]. Especially in recent times, the circumplex model comprising a pleasantness dimension and an awareness dimension suggested by Russell [13] has been validated in terms of its universality and robustness by many previous researches [24,25].

Thus, since Schlosberg's research [22,23], many researches have been conducted attempting to find an affective meaning dimension (psychological variable) relating to the recognition of facial expressions. However, the visual information related to the recognition of facial expressions has been little researched. This means that the relationship between the psychological variable and the physical variable has not yet been identified regarding human cognizance of emotion by facial expression.

Yamada [26] conducted a study to clarify visual information (the physical variable) related to the cognition of facial expressions using a line-drawing figure in which eight points of the eyebrows, eyes and mouth are manipulated. From the results, two physical variables have been found: slantedness, meaning the curve and indication of face elements; and openness and curvedness, meaning the level of curve and openness of facial elements. In addition, they have suggested that there are strong relationships between slantedness and the pleasantness dimension, and between openness and activeness [27,28]. Based on this knowledge, they proposed that there are three processes used to cognize facial expressions: (1) acknowledgement of visual information (the physical variable) of the face, (2) evaluation of affective meaning based on the physical variable, and (3) judgment of the emotional category based on affective meaning [10].

Moreover, from similar research using actual human faces, it has been suggested that there are three physical variables of visual information – openness, slantedness of mouth, slantedness of eyebrows and eyes [29] – and that the same results as those in a three-dimensional structure would be produced in the case of using a line-drawing face [30]. Furthermore, it has been determined that there is a strong relationship between the slantedness of the mouth and the pleasantness dimension, and between the slantedness of the eyebrows/eyes and activeness, as well as a moderate relationship between openness and both forms of slantedness [31]. Through competitive research using line-drawing faces and actual human faces, a strong relationship was also found between the openness of the eyes and mouth and pleasantness [32]. In this respect, there is a close relationship between visual information (the physical variable) and emotional information (the affective variable). The objective of this thesis is to validate the relationship between the physical variable and the affective variable discovered by previous researches using geometrical faces, and to apply the existing knowledge to robot facial design. Clarification of this relationship is one of the most important aspects for research on cognition of facial expression. The geometrical face used for this thesis is comprised of the minimum necessary elements for recognizing the face, and the elements are transformed geometrically to form the various facial expression patterns. The author introduces the physical variables, slantedness and openness, to the geometrical transformation. These facial patterns are classified by basic emotions, and evaluation of the relationship between the physical and affective variables is conducted by applying principal component analysis to the facial expression space centered on physical variables. Based on the results of the research, the author finally developed a model to create facial expressions.

In addition, in this thesis the author researched the neutral face, a concept that has rarely been mentioned by previous researches. In recent research, it has been suggested that the neutral face does not strictly speaking show a neutral emotion, but rather conveys some meaning concerning an actual circumstance of life.

By not using a realistic-looking human face, but rather a face made with limited elements and employing geometrical transformation, the relationship between the elements and factors used in making facial expression is shown more clearly. In addition, the result of this relationship expands in application to not only robot facial design, but also to medical fields such as curing cognitive impairment of facial expression. Thus, it is aimed to apply the results of this research to other fields.

2. **Experiment Concerning Cognition and Structure of Facial Expressions.** In this chapter, an expression pattern is generated using the geometrical transformation of a face made with the minimum necessary elements, the eyes and the mouth. Elements are transformed by the parameters of slantedness and openness.

The category of basic emotions is used to classify the facial patterns. The classified facial expression patterns are evaluated by analyzing the spatial distribution of the facial expression patterns generated based on the values of the transformation parameters.

These processes are aimed at discovering the geometrical, spatial and quantitative relations between the elements and the factors used to make facial expressions.

2.1. **Making expression patterns.** The elements composing the face are limited to just three: the two eyes and the mouth, composed of precise circles and placed on the top of the upside-down triangle, the face figure (Figure 1). Facial expression patterns are made by adding transformations to the three elements within the two parameters of slantedness and openness, comprising the physical variable for cognition of facial expressions. Slantedness of the eyes is a parameter that expresses the curve according to the opening of the eyes by their rotational deformation, while slantedness of the mouth expresses the rise or fall of the corners of the mouth. Openness is a parameter that expresses the change in the opening state of the eyes and mouth by the change in the vertically scaling transformation of the precise circle. Figure 2 and Figure 3 show the changes to the eyes and mouth according to the value of the parameters. The eyes make 19 patterns and mouth makes 7 patterns as shown in Figures 2 and 3, making a total of 133 expression patterns. The facial expression is assumed to be completely facing the observer, and all faces are symmetrical.

Thus, each facial expression is defined by four values: two parameters of the eyes and two of the mouth, namely slantedness and openness respectively. So, the coordinates of one face can be shown as in the following mathematical expression.

$$\vec{f_i} = \begin{pmatrix} E_{si} \\ E_{oi} \\ M_{si} \\ M_{oi} \end{pmatrix}, \quad i \in \{1, 2, \ldots, n\}$$

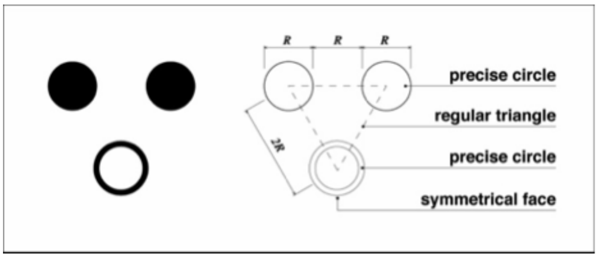

FIGURE 1. Example of figure

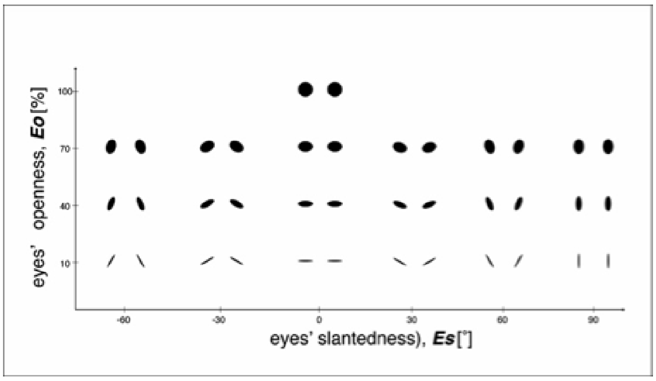

FIGURE 2. Transformation of eyes by each parameter

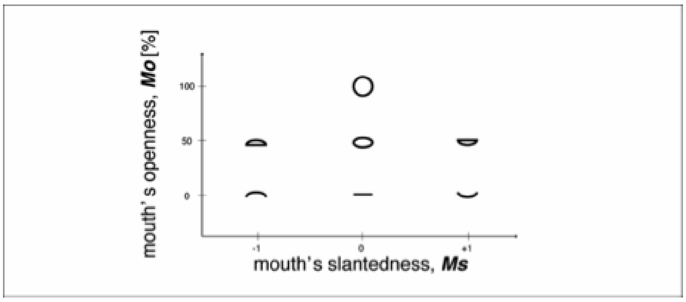

FIGURE 3. Transformation of mouth by each parameter

The above mathematical expression shows the coordinates of the i-th facial expression, where E_s and E_o represent the eyes' slantedness and openness respectively, and M_s and M_o represent the mouth's slantedness and openness respectively.

2.2. **Classification of facial expression patterns.** The obtained expression patterns are classified by emotional category. For the emotional categories, the author uses the six basic emotions (happy, angry, sad, disgust, fear and surprised) advocated by Ekman and many other researchers. In this thesis, the author additionally utilizes a neutral (pleasant) emotion, displaying no emotion but showing a pleasant expression, and a neutral (unpleasant) emotion, showing no emotion but displaying an unpleasant expression, in order to research the facial expressions of neutral emotions. Clarification of the neutral face is important for robot faces, especially for humanoid robots without the function of forming facial expressions. In total, the eight emotional categories are defined.

Classification of facial expression patterns is conducted through an identification task. There are three rules for this task as follows: (1) the answerer must choose one emotion category for one face; (2) the answerer may adopt the same emotion category for more than one face; (3) the answerer does not need to select an emotion category if no category fits the face.

2.3. **Distributing facial expression patterns in mathematical space.** As described in 2.1, each expression is defined by four-dimensional coordinates. Based on these coordinates, the author distributes the classified facial expression patterns in four-dimensional space. The facial patterns distributed in space are the faces selected by more than $p/2$ answerers (p is the maximum number of answerers selecting the face as the emotion category).

After creating the facial expression space, analysis is applied to the space and the dimensions of the space are reduced to render it perceptible to the human eye. Through this analysis and visualization, the author can observe the difference in spatial distribution and parametric values of each facial pattern.

3. Result of Classification and Spatial Distribution of Facial Expressions.

From the results of the principal component analysis, the face distribution space is composed of three variables: openness of the mouth, slantedness of the eyes, and openness of the face. Moreover, this result almost completely concurs with expression distributions in the space composed of the emotional meaning dimension in previous research, and shows similarity to the results of expression cognition research using faces of actual human beings.

In addition, the research of the past is consolidated, and 10 basic facial expressions happy, angry, angry*, sad, disgust, fear, fear*, surprised, neutral (pleasant), and neutral (unpleasant) are advocated.

3.1. **Three-dimensional space for distribution of face.** The identification task was undertaken by 140 men and women ranging in age from their teens to their 60s. (average age in their 20s). The results of the principal component analysis of four-dimensional space are shown in Table 1. Four-dimensional space can be reduced to three-dimensional space from the result of the cumulative proportion from principal component-1 to principal component-2, shown to be 0.807. In addition, the value of each principal component is shown in Table 2. Principal component-1 was judged to mean the slantedness of the mouth; principal component-2 shows the slantedness of mouth; and principal component-3 shows the openness of the face, meaning openness of both eyes and mouth, according to this value. This result corresponded to the three types of visual information (the visual variable) that had been obtained by previous researches [12-16].

Table 1. Result of principal component analysis

Principal component	1	2	3	4
Standard deviation	1.119	1.034	0.951	0.873
Cumulative proportion	0.313	0.581	0.807	1.00

Table 2. Meaning of each principal component

Principal component	1	2	3
Slantedness of eyes	0.280	−0.773	−0.298
Openness of eyes	0.557	0.125	0.749
Slantedness of mouth	0.674	−0.137	−0.160
Openness of eyes	−0.396	−0.606	0.570
Meaning	Mouths slantedness	Eyes' slantedness	Faces openness

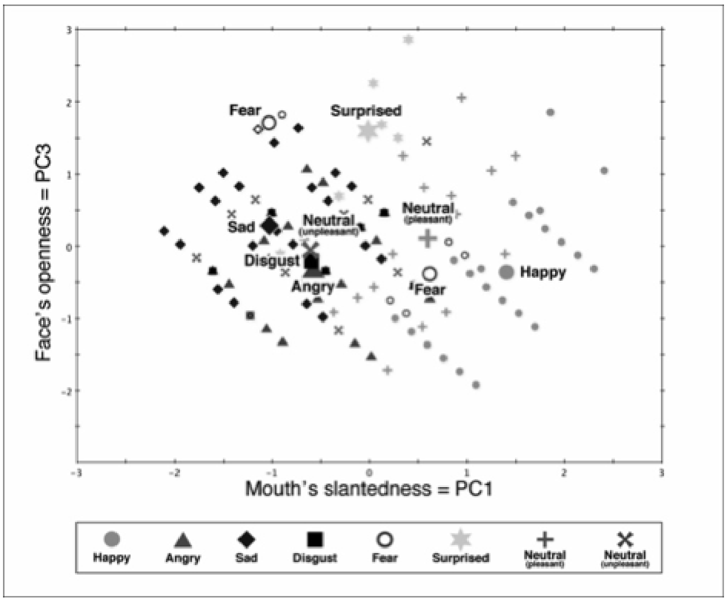

FIGURE 4. Projection plane of three-dimensional space for facial expression composed of slantedness of the mouth and openness of the face

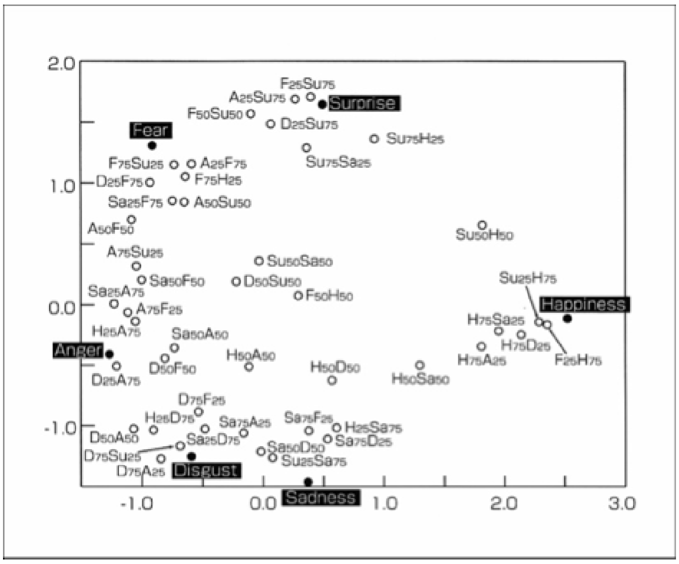

FIGURE 5. Circumplex mode constructed by Takehara and Suzuki (2001)

To assess the relationship between the emotional meaning dimension obtained by this research and the visual information dimension obtained by previous researches, the author compared two planes, a projection plane of three-dimensional space obtained by this research comprising slantedness of mouth and openness of face, and a plane comprising the pleasantness dimension and the activeness dimension [10], which have strong relationships with the slantedness of the mouth and the openness of the face [17,18]. The former plane is shown in Figure 4, and the latter in Figure 5. Each facial expression is assigned a weight according to the number of selections. An important point in Figure 5 and Figure 6 is that the average coordinates of each emotion category took these weights into consideration.

Comparing Figure 4 and Figure 5, the distribution of happy, surprised, and fear can be seen to almost correspond, and in addition, angry, sad, and disgust were also seen

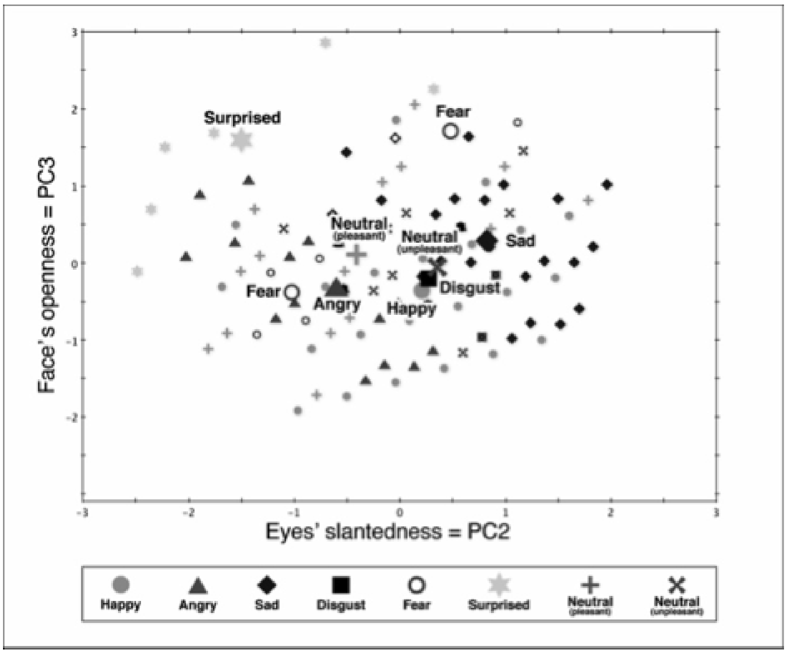

Figure 6. Projection plane of three-dimensional space for facial expressions composed of the slantedness of the eyes and the openness of the face

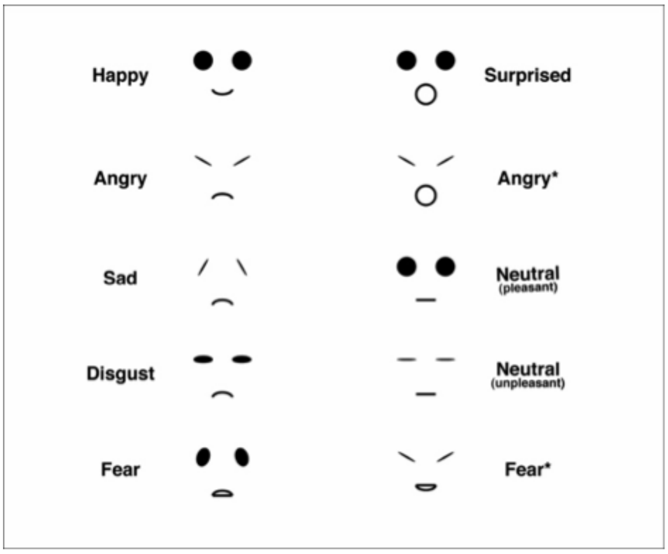

Figure 7. Typical facial patterns of 10 basic facial expressions

to correspond in terms of closeness of distribution. Moreover, fear could be seen to separate into two clusters in terms of distribution, which could be read in Figure 4. As mentioned above, the author determined that the distribution of the facial expressions in three-dimensional space obtained through this thesis was valid.

In addition, angry, sad and disgust were separately observed by constructing and observing a projection plane of three-dimensional space comprising slantedness of the eyes and openness of the face (Figure 6). From this result, by considering the third dimension, the slantedness of the eyes, the distribution of each facial expression was easy to separate and read. Thus the author discovered that the visual information dimension (physical variable) comprises three variables for cognizance of facial expressions.

3.2. **Eight facial expressions and two neutral facial expressions.** In addition to the observation of face distributions in space, the author found 10 basic facial expressions, eight basic facial expressions: happy, angry, angry*, sad, disgust, fear, fear*, and surprised; and two neutral facial expressions: neutral (pleasant) and neutral (unpleasant), according to the parametric values and actual facial patterns. Figure 7 shows each typical facial expression. The difference between angry and angry* is especially apparent in terms of the openness of the eyes and mouth, so angry can be separated in terms of the facial expression showing the anger emotion. Moreover, it can be seen that fear and fear* can be separated because the slantedness of the eyes and the mouth indicate an opposite value.

Furthermore, these facial expressions are distributed in three-dimensional space based on continuous geometrical transformation of the eyes and mouth, and it is understood that each facial expression generates a network comprising a visual and a physical variable (geometrical transformation).

4. **Discussion.** In this chapter, a tetrahedral model for making facial expressions is advocated. This model comprises the geometrical and spatial relationships among the 10 facial expressions, and the actual facial patterns and the parametric values of each element.

4.1. **Relationship between the visual variable dimension and the affective meaning dimension.** Through the facial expression pattern presented in this thesis, the visual variable dimension was obtained, namely, the slantedness of the eyes, the slantedness of the mouth, and the openness of eyes and mouth. Moreover, by observation and comparing with three-dimensional space and the results of previous research, it was found that there is a strong relationship between the slantedness of the mouth and the pleasantness dimension, and the openness of the eyes and mouth and activeness, as indicated in previous research.

In addition, based on observation of the distribution in three-dimensional space, the slantedness of the eyes is an effective means of discerning the distribution areas of the facial expressions, especially angry, sad and disgust. Thus, the third effective variable's dimension serves to aid cognition of facial expression, and bears a strong relationship with the judgment of angry, sad and disgust.

4.2. **Limitation of facial elements and cognition of facial expressions.** In many previous researches, various experiments on recognition of facial expressions was conducted using actual human faces and pictures or line-drawing faces closely resembling the human face. On the other hand, in this thesis, the minimum elements needed to recognize the face as a face were selected, and the face used for the experiment consisted of only two eyes and a mouth. The eyes and the mouth were used to make facial patterns through geometrical transformations based on precise circles.

From the results, it was found that human beings could recognize faces and judge facial expressions and emotions even when observing a face composed of limited elements subject to geometrical transformations, as well as being able to recognize the expressions of actual human beings.

Thus, it is possible to read emotion sufficiently, not only from the facial expression of an actual human being, but also from the expression made by a geometrical transformation (rotation and vertically scaling transformation) of the minimum geometrical elements (two eyes and a mouth) needed to recognize a face.

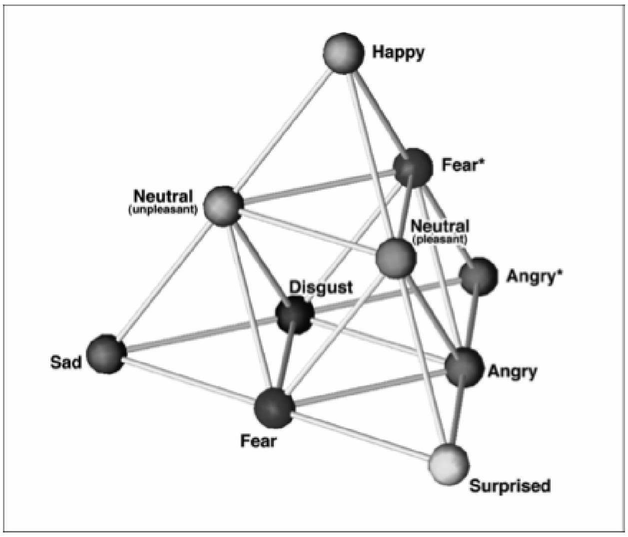

FIGURE 8. Tetrahedral-model on structure of facial expressions

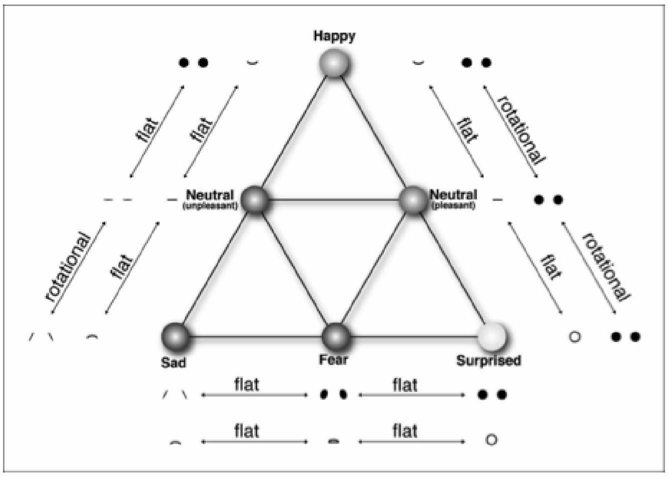

FIGURE 9. Happy-Sad-Surprised surface of tetrahedral model

4.3. **Tetrahedral model to make facial expressions.** According to the results and discussion, a tetrahedral model used to make facial expressions is advocated using the 10 basic facial expressions. The model's structure is shown in Figure 8. This facial model's target is a face made with two eyes and a mouth, and facial patterns made by rotation and vertically scaling transformation of the elements. The 10 emotions are placed in four locations, on top of the body and at a middle point on each side. The position in which each expression is produced is expressed with the ball. The sides between the balls are the axes of transformation of the eyes and the mouth in a constant direction. The actual transformation of the elements is shown in Figures 9-11.

These figures show the equilateral triangle plane made from each of the three tops of the tetrahedral model. Rotation and vertically scaling transformation add the eyes, while vertically scaling transformation alone adds the mouth, along the axis (side) connecting each expression. By these transformations and the relationships between each parametric value, the facial expressions can be made to change.

To take the triangle in Figure 9 as an example, on the side connecting happy and sad, first of all the eye flatness rate is changed to 10% (this forms the eye for neutral

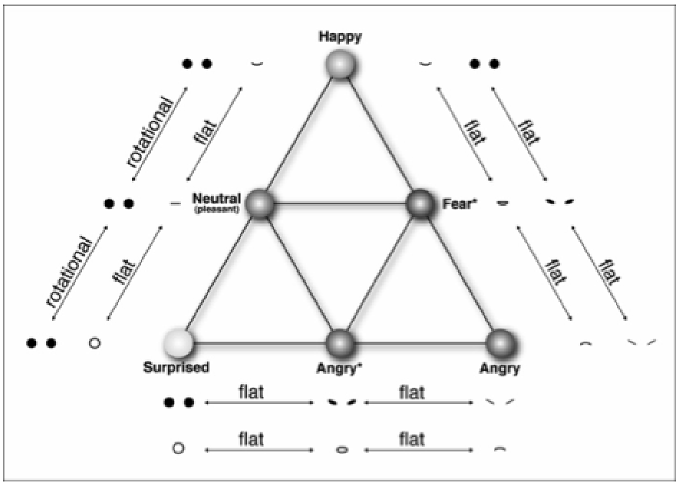

FIGURE 10. Happy-Surprised-Angry surface of tetrahedral model

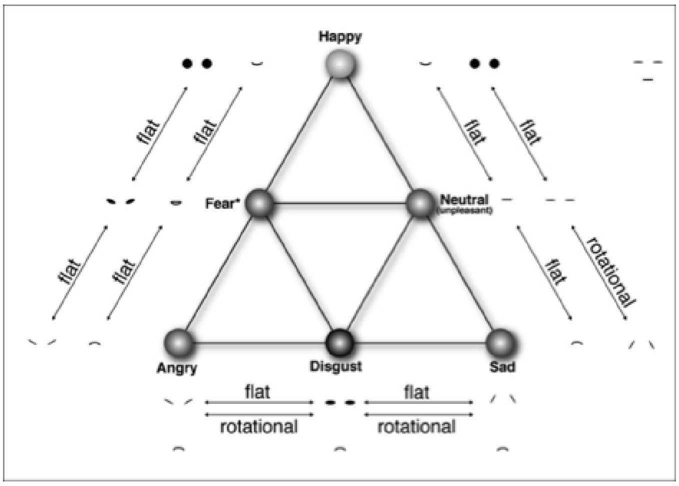

FIGURE 11. Happy-Angry-Sad surface of tetrahedral model

(unpleasant)), and secondly, rotation is added and the angle of the eye is changed to −60 degrees, creating the eye for sad. Meanwhile, the mouth's form is changed to flat, (neutral (unpleasant)), after that it is changed to form the sad face. The happy face's mouth and the sad face's mouth indicate fully opposite values. As shown in Figures 9-11, the topological distance between each emotion is equal, and each facial expression changes to the adjacent facial expression along the side connecting the emotions.

The tetrahedral model can be applied to all face making facial expressions by using geometrical elements and their transformation. For instance, facial expression is assumed to become very important in future communications between humanoid robots, as well as for communication with human beings. In such situations, making facial expressions of humanoid robots is easier using the tetrahedral model, because this model has succeeded in creating facial expressions by geometrical elements and transformation. As well as in the robot field, the application range of the tetrahedral model in the future is thought to be vast, encompassing the realm of healing, curing cognitive impairment, and so on.

4.4. **Facial expression of neutral facial expression.** In this paper, the neutral (pleasant) and neutral (unpleasant) expressions were added to the classification of facial expressions. These expressions were found to exist even though they do not show a specific emotion, and these neutral facial expressions can be generated through transformation of facial elements. Moreover, according to the facial pattern, the neutral face can be divided into two facial expressions, showing pleasant and unpleasant emotions respectively. From the results of observing the spatial and geometrical differences between faces, and the tetrahedral model, the author defined the neutral (pleasant) facial expression as between happy and surprised, and the neutral (unpleasant) expression as between happy and sad.

5. **Conclusion.** In this research, the authors succeeded in creating facial expressions made with the minimum necessary elements for recognizing a face, and enabling human recognition of the expressions created. The elements used for the minimal face were two eyes and a mouth made by precise circles and transformed to make facial expressions geometrically, through rotation and vertically scaling transformation. The facial expression patterns made by the geometric elements and transformations comprised three dimensions of visual information (visual variables) that had been suggested by many previous researches: slantedness of the mouth, openness of face, and slantedness of the eyes. Thus the results of this research indicate that human beings can classify expression patterns of minimal faces to particular emotional categories just as they would with an actual human face. In addition, the relationships between visual affection dimension and the affective meaning dimension also corresponded to the results of the previous researches. These relationships were strong between the slantedness of the mouth and pleasantness; and between the openness of the face and activeness; and the existence of a third affective variable strongly related to the slantedness of the eyes was also suggested.

The authors found that facial expressions could be classified into 10 different facial expressions: happy, angry, sad, disgust, fear, surprised, and angry*, fear*, neutral (pleasant) showing a positive emotion, and neutral (unpleasant) showing a negative emotion. These facial expressions are composed by different geometric transformations and combinations of the eyes and the mouth. Furthermore, the authors discovered a tetrahedral model that could express most clearly the geometric relationships between the facial expressions. This model is structured in the form of a tetrahedron, with each facial expression located on the top or the middle of the sides of the tetrahedron. Each side connecting faces is an axis determining the rotation and vertically scaling transformation of the eyes and the mouth.

In future, it hoped to research the affective dimension for recognition of facial expressions and to clarify the relationship between the visual variable dimension and the emotional information dimension, and to actually apply the tetrahedral model to humanoid robots and to other wide-ranging fields.

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