

Development of Interactive Industrial Design Support System Considering Customer's Evaluation* (Shape Design of Eyeglass Frame)

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To respond to rapidly changing and diversifying customers' requirements, an industrial design support system for eyeglass frames which allows the customer to participate in the industrial design process was developed. This system is based on the Interactive Evolutionary Computing (IEC) technique so that a customer can interact with the system to express his or her Kansei requirements through images. The design of an eyeglass frame cannot be determined in isolation but rather must be determined by considering its appearance on the customer. In the developed system, the user evaluates each sample suggested by the system and narrows down the candidate gradually. Its usefulness was demonstrated by operational experiments and questionnaires.

Key Words: Design Engineering, Industrial Design, KANSEI, Interactive, Design, Interactive Evolutionary Computing (IEC), Eyeglasses Frame

1. Introduction

Today's consumer market is full of many similar products. This phenomenon has encouraged customers to diversify their requirements and to become stricter when evaluating products. Furthermore, network technology such as the Internet has globalized the market, accelerating even further the diversification of customers' requirements. It has thus become necessary to precisely identify various customer requirements and to reflect these requirements in the design of a product⁽¹⁾.

This shifting situation can be described using the analogy of 'vectors' and 'scalars'. Conventional production can be viewed as dealing with 'scalars': customer requirements were homogeneous and the emphasis was placed on improving technology to meet such requirements. More recently, however, customer requirements

have become increasingly heterogeneous, and they are more appropriately described as 'vector' quantities, with dynamic characteristics, rather than 'scalar' quantities.

A product has various requirements such as functionality, cost, reliability, aesthetics, and so on. Taking the personal computer as an example, it can be said that requirements like functionality and cost have become largely saturated in today's market so that added values like aesthetics have become important considerations. A product's aesthetic appeal is a subjective judgement not easily laid out in the form of a product specification and its evaluation cannot be readily quantified. The authors have previously proposed a method that quantifies differences in people's subjective KANSEI (psychological feeling or image of a product) towards industrial designs, based on the Semantic Differential (SD) method and incorporating evaluation experiments using 'impression words'. We furthermore developed an industrial design support system employing impression words and applied it to the exterior design of a cell-phone⁽²⁾.

Human evaluation, including people's impressions of and preferences toward industrial designs, depends on such factors as time or the situational context and differs among individuals. Such items are generally difficult to quantify. Furthermore, with the rapid development of network technology, customers' demands are changing and diversifying on a day-to-day basis. This situation has led

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to increasing importance being placed on methods for subjective evaluation. Made-to-order designs provide one solution to the diversification of customer requirements: the designer lays out the design direction only after the individual customer's needs are well understood. But made-to-order designs accompany such problems as cost and time. Consequently, there has arisen the need for design support systems that can meet changing and diversifying customer requirements on an interactive basis.

In this paper, we introduce an industrial design support system where the customer can participate in the design process and express his or her requirements such as the KANSEI image by interacting with a computer. In this system, a person's subjective evaluation of design samples is regarded as a fitting function, for which the system calculates suitable design parameters using the Genetic Algorithm (GA)⁽³⁾. The parameters calculated using GA are expressed in the proposed design samples. Through the interaction of design samples and the customer's subjective evaluation over several generations, design samples evolve toward the customer's desired design.

Such an iterative approach based on GA is called Interactive Evolutionary Computing (IEC). IEC has been applied to various fields such as design, art, computer graphics, and music. There have also been applications to design support systems⁽⁴⁾⁻⁽⁷⁾.

There are two reasons for employing GA. First, it is difficult to express human subjective evaluation as a mathematical formula, and even if this were possible, there may exist multiple solutions. GA can globally and effectively search for solutions in such cases by simulating genetic processes. Secondly, our system's goal is to assist customers with little or no design knowledge in exteriorizing their requirement images. Studies in which IEC with GA was applied to designing support systems⁽⁸⁾ have shown GA to be effective in supporting users who are not professional designers.

We developed a system for designing the shape of an eyeglass frame, and call it the Interactive Design support System for eye Glass Frames (IDS-GF). In addition to holding the optical lens in place, an eyeglass frame must also be aesthetically appealing⁽⁹⁾. It is not so easy for customers who are not designers to provide a clear aesthetic image of what they want. Yet diversifying tastes have made it a necessity to identify the customer's requirement (i.e., his/her image). IDS-GF helps the customer to express his/her image and to design an eyeglass frame based on that image. The user arrives at his/her final design by an iterative process of evaluating successive generations of design samples produced by the system.

The following section describes the IDS-GF as well as the experiments for its evaluation. The system's effectiveness is then discussed based on experimental results. From records of the users' operational processes, we in-

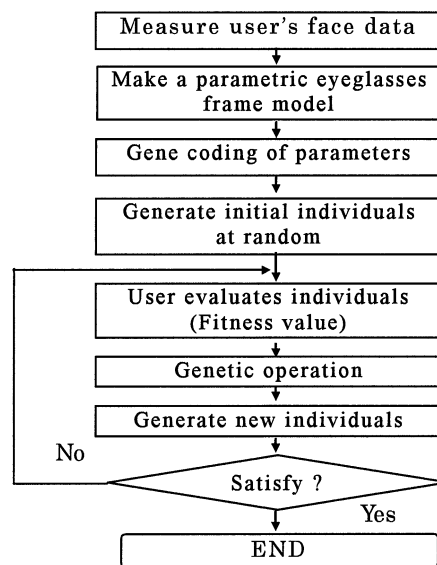


Fig. 1 Flow chart for developed system

investigate the relative importance of the various evaluation characteristics to users. Finally, we discuss the concepts of 'rough' and 'detail' evaluations, which refer to the contextual field the user appears to select when making an evaluation of the design samples.

2. Interactive Design Support System for Eyeglass Frames

The flow chart for the IDS-GF is shown in Fig. 1. After an image of the customer's face is captured with a digital camera, the facial parameters are measured using image processing. A parametric model for the eyeglass frame is then generated from the extracted facial parameters; there are ten design parameters. The ten parameters are coded to a bit array, called a gene array. The values of the gene array are randomly initialized to generate the first-generation design samples. The customer then evaluates and scores each generated design sample based on his or her degree of satisfaction. These scores are regarded as fitness values in the GA. Using GA and the user's scores, the system then calculates the next generation's gene arrays and creates the next-generation design samples. The user repeats these operations until he or she arrives at a satisfactory sample.

2.1 Measurement of facial data

The face measurement system we developed extracts from the captured facial image the height of the face: F_h , the width of the face: F_w , the x -coordinate of the right eye: ey_x , the width of the eye: ey_w and the height of the eye: ey_h . Figure 2 shows the facial parameter measurement system. The user extracts the parameters by pointing with a mouse. The system normalizes the facial area by an affine transform using the line connecting the two eyes, le_x , and the bisecting line normal to le_x .

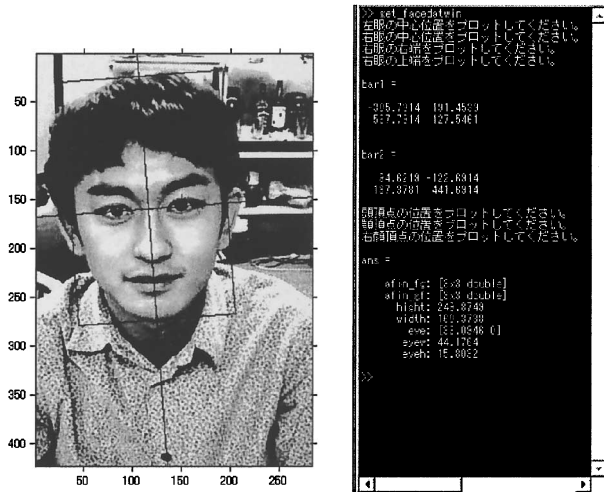


Fig. 2 A face parameters measurement system

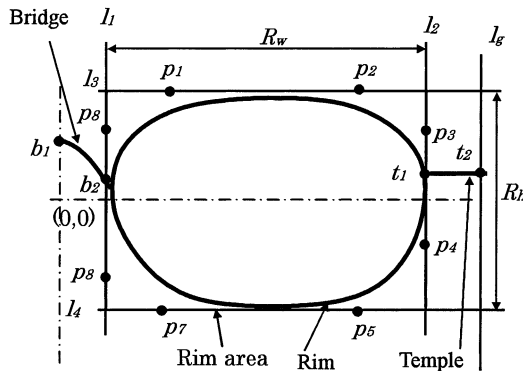


Fig. 3 A parametric eyeglasses frame model

2.2 Parametric model of eyeglass frame

The design parametric model is generated from the customer’s facial measurements (Fig. 3). The eyeglass frame model consists of a rim, a temple and a bridge. The shape of the rim is formed by Riesenfeld spline curves⁽¹⁰⁾. A rectangular region bordered by the lines $l_i (i = 1, \dots, 4)$ is defined around the user’s eye as follows.

$$l_1 = e_x - \frac{R_w}{2}, \quad l_2 = e_x + \frac{R_w}{2} \tag{1}$$

$$l_3 = \frac{R_h}{2}, \quad l_4 = -\frac{R_h}{2} \tag{2}$$

where R_w is the region’s width, R_h is the region’s height and e_y is the central position of the eye. The spline control points p_1 to p_8 are positioned on the borders of the rim region. The rim curve is obtained as follows.

$$\begin{cases} x(t) = \sum_{i=1}^8 x_i B_{i-2,4}^c(t) \\ y(t) = \sum_{i=1}^8 y_i B_{i-2,4}^c(t) \end{cases} \tag{3}$$

where x_i and y_i are the coordinates of the spline control points and $B_{i,2m}^c$ is a closed spline function. The bridge is formed by a quadratic curve and the temple by a straight line.

2.3 Gene coding

The parametric model consists of ten parameters: the coordinates of the spline control points $p_i (i = 1, 2, \dots, 8)$, the width of the rim R_w and the height of the rim R_h . The vector for the coordinates of the spline control points P is obtained as follows.

$$P = L + QR \tag{4}$$

$$P = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \\ x_5 & y_5 \\ x_6 & y_6 \\ x_7 & y_7 \\ x_8 & y_8 \end{bmatrix} \quad L = \begin{bmatrix} l_1 & l_3 \\ l_2 & l_3 \\ l_2 & l_4 \\ l_2 & l_4 \\ l_1 & l_4 \\ l_1 & l_4 \\ l_1 & l_4 \\ l_1 & l_3 \end{bmatrix} \quad Q = \begin{bmatrix} q_1 & 0 \\ -q_2 & 0 \\ 0 & q_3 \\ 0 & -q_4 \\ -q_5 & 0 \\ q_6 & 0 \\ 0 & -q_7 \\ 0 & q_8 \end{bmatrix} \quad R = \begin{bmatrix} R_w & 0 \\ 0 & R_h \end{bmatrix}$$

where $q_i (i = 1, 2, \dots, 8)$ is the distance between a spline control point p_i and the nearest corner of the rim region, normalized from 0 to 0.5. Each parameter is coded into a binary string. Each q_i value is assigned 6 bits while the width R_w and height R_h of the rim are each assigned 8 bits. Thus the total length of the bit string is 64 bits.

2.4 Sample number and fitness value

Six frames are generated in one generation. This comes from a consideration of the established limitations of human memory, which enable the comparison of a maximum of nine objects at one time⁽¹³⁾. We thus considered six to be the suitable number of design samples provided for evaluation in a single generation. The customer evaluates each frame according to a five-grade scale based on his/her degree of satisfaction. The evaluation score is regarded as a fitness value in the GA.

2.5 Genetic operator

The genetic operation is based on roulette selection, uniform crossover, and mutation. The probability of mutation is assumed to be 0.08 and the generation gap 0.8.

2.6 System interface

Figure 4 shows the GUI interface of the IDS-GF. Six design samples, with eyeglasses superimposed on the facial images, are displayed based on the facial measurement data and the generated design parameters. Slide-bars are provided for evaluating each design sample. When the six evaluations are completed, the user clicks on the ‘Next’ button, whereupon the system generates new design samples. The user and system repeat this process until the user finds a satisfactory design.

3. Experiments

In order to verify the effectiveness of our developed system and to analyze tendencies of subjective evaluation, we carried out the following experiments. In each experiment, eight male subjects in their twenties, who are beginning students of industrial design, participated.

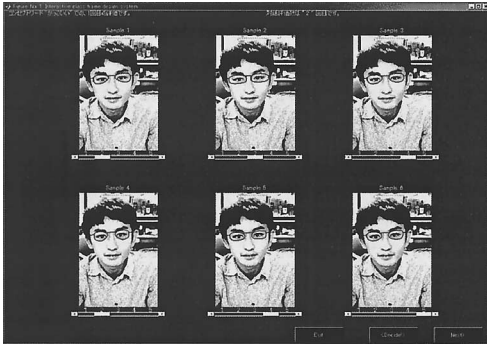


Fig. 4 Design support system for shape of eyeglasses frame

3.1 Experiment of system's operation

We carried out an experiment of the developed system's operation. The experimental procedure is as follows.

- (i) Capture an image of the subject's face by digital camera and save it as a picture file.
- (ii) Measure facial parameters using the image-processing face measurement system.
- (iii) Ask the subjects to give three concept words that express their required image, such as 'beautiful,' 'elegant,' or 'smart,' in order to encourage the subject to develop a clear mental image.
- (iv) Using a questionnaire, measure the subject's intensity (or clarity) of the mental image according to a three-grade scale.
- (v) Allow the subject to practice operating the system until he/she becomes used to it.
- (vi) Each subject then operates the IDS-GF system three times for each of the three concept words. Thus each subject carries out a total of nine trials, each trial consisting of ten iterative steps (generations).

The number of generations to convergence was set at ten to see whether a subject will successfully arrive at a satisfactory sample within that number, which we considered to be a reasonable cycle of iterations. In a preliminary study involving five subjects (different from the subjects in this experiment; all male in their twenties), we obtained 8.6 as the average number of generations in which the subjects arrived at a satisfactory design. Other studies^{(8),(11)} have shown that 5 to 15 generations is a suitable convergence condition.

3.2 Experiment for evaluation of design results

3.2.1 Experiment 1 The subjects evaluate their degree of satisfaction for the finally obtained design sample according to five-grade scale in a questionnaire given at the end of each operational trial. The five-grade scale consists of 1) unsatisfied, 2) somewhat unsatisfied, 3) neither satisfied nor unsatisfied, 4) somewhat satisfied and 5) satisfied.

3.2.2 Experiment 2 In order to check the validity of the design results, the obtained design samples and randomly made design samples were compared. This ex-

Table 1 ANOVA table for the averages of satisfaction value

	SS	df	MS	F
Model	21.8	7	3.11	8.96
Error	22.2	64	0.34	
Total	44.0	71	0.62	

periment took place a week after Experiment 1. Thus, the purpose is to evaluate the temporal stability and objective validity of the obtained results. Experiment 2 was conducted as follows.

- (i) Select the three highest-rated design samples (i.e., giving the most satisfaction) among the design results. These samples are called 'satisfactory samples'.
- (ii) Generate seven samples at random; these are called 'random samples'.
- (iii) Compare pairs of 'random' and 'satisfactory' samples according to a five-grade scale, with the following grading system: compared to the right sample, the left sample is (1) about the same; (2) a little better; (3) better; (4) quite better; and (5) much better. The samples were presented in a random manner to prevent the order of presentation from influencing the results.

3.2.3 Open questionnaire The subjects were asked to comment freely regarding their impression of the system in a questionnaire after completion of the entire set of experiments.

4. Experimental Results and Discussion

4.1 Validity of design results

Results of Experiment 1: Using the developed system, the user may be expected to arrive at a satisfactory result via interaction with the system. The questionnaire concerning degree-of-satisfaction was obtained in Experiment 1. The average degree-of-satisfaction shows a relatively high dispersion, with a standard deviation of 0.72. The ANOVA table for the average degree-of-satisfaction for a subject is shown in Table.1. According to the ANOVA, the difference among the average degree-of-satisfaction for each subject had a 1% statistical significance.

To examine the cause of this dispersion, we compared the open questionnaire responses of Subject 3, who scored the highest satisfaction average of 4.9, and Subject 4, who scored the lowest average of 2.6. Subject 3 stated that he evaluated each design sample generated by the system based on a clear mental image he had. Meanwhile, Subject 4 stated that he did not have a clear image and that he had difficulty evaluating each sample. What this means is that a user who possesses a clear mental image of his/her requirements will try to create a design solution that approaches this image. A user who does not have a clear im-

age expects the program to present him/her with a design that meets his/her requirements. In other words, there exist differences among users that can be described as ‘convergent’ and ‘divergent’ tendencies. There is a 0.86 correlation between the subject’s intensity of his mental image and his average degree-of-satisfaction. Thus our system proves to be effective for a user who holds a clear mental image of his/her requirements, but if not, he/she may not obtain a satisfactory design.

Results of Experiment 2: If the system-generated design results are valid, they should provide a higher satisfaction than randomly generated samples. Based on the values obtained from Experiment 2 (comparison of pairs), the degree-of-importance is calculated for the ‘satisfactory’ and ‘random’ samples. The Degree-of-Importance is calculated using the Analytic Hierarchy Process (AHP)⁽¹²⁾.

Among the three samples that scored the highest, there were an average of 2.6 ‘satisfactory’ samples (for the eight subjects). The random samples had an average degree-of-importance of 0.08 while the three ‘satisfactory’ samples had that of 0.2. According to the T test, the difference between the ‘satisfactory’ and ‘random’ samples had a 0.5% statistical significance. The validity of our system is thus verified.

4.2 Convergence of solution

Convergence of the solution is an important indicator when optimizing a system. What we seek to optimize in this study is the human psychological process of evaluating a proposed product, and convergence of a solution means bringing the solution increasingly closer to some image held in the subject’s mind. If the solution converges to the user’s image, the presented samples should become increasingly similar to each other in the later generations. We employed the variance of design parameters as an indicator of similarity. The sum of the variances of all design parameters in the *j*th generation, *Tvar_j*, is obtained as follows.

$$Tval_j = \sum_i Var(F_{ij}) \tag{5}$$

where *Var(F_{ij})* is the variance of the *i*th design parameter in the *j*th generation. Figure 5 shows the average *Tvar_j* for all subjects over the generations; it decreases with generations. This means that the solution gradually converges to the user’s mental image without getting into a local minimum.

It can be seen, however, that a small increase occurs at the 8th generation. This is thought to be caused by the users hoping to obtain even better designs although a satisfactory result had already been reached. In fact, a few subjects stated in the open questionnaire that they deliberately gave a high score to an ‘inferior’ design when they had already obtained a satisfactory result, hoping that this might produce an even better design.

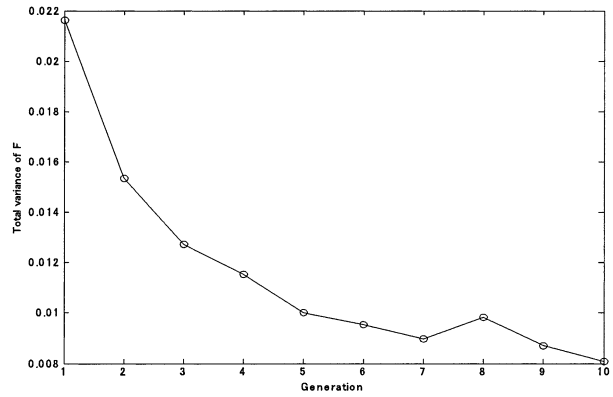


Fig. 5 Total variance of feature parameters

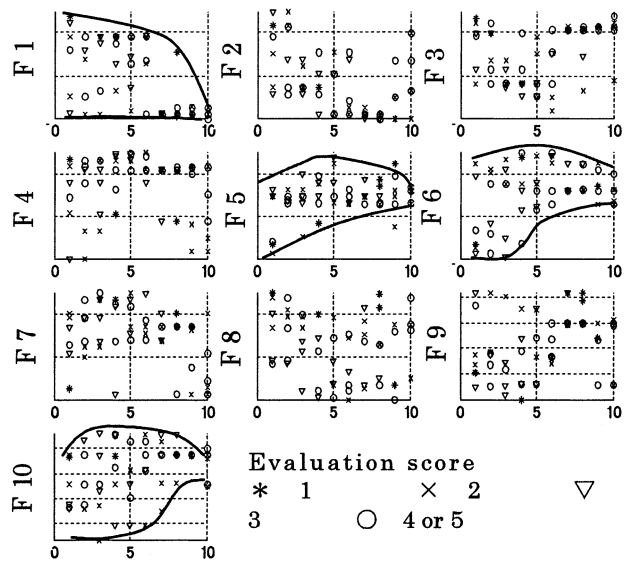


Fig. 6 Distribution of feature parameters (Subject 1)

In this instance, the user is not evaluating the presented alternatives in a straightforward manner, but instead using the evaluative act as a kind of meta-operator to try to prod the system into producing better solutions.

4.3 Relative importance of features

In order to examine the interaction between the system and user, we analyzed how the feature parameters for each design sample evolved over the generations along with the user’s evaluation scores. Figure 6 shows the changes in feature parameters for subject 1. The horizontal axis represents generations and the vertical axis is the parameter value. There are ten graphs, each one for a different parameter. The four marker types indicate the user’s evaluation scores for the design sample that contains that parameter value.

It can be seen from Fig. 6 that feature parameters 1, 5, 6 and 10 converge to a steady value. Assuming that convergence of a solution indicates that the user has arrived at a satisfactory sample, we see that the parameters differ in their relative importance. In other words, a subject gives different weights to the ten parameters, paying more

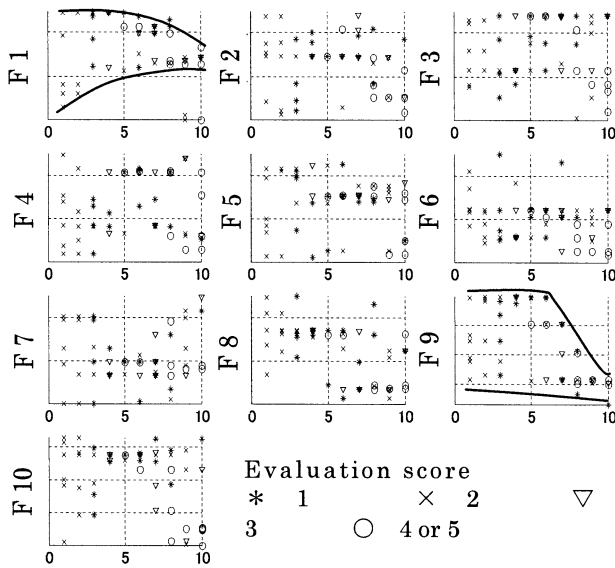


Fig. 7 Distribution of feature parameters (Subject 5)

attention to some than the others.

Figure 7 shows the change in feature parameters for another subject (subject 5). A comparison of Figs. 6 and 7 shows that different subjects pay attention to different features. In other words, different subjects have different frameworks for evaluating design samples.

By assigning weights to parameters based on their relative importance, therefore, the system can be 'tailored' to individual users. Reference (14) has proposed Online Knowledge Embedding EC, applying it to a face montage system. Here the user selects parameters that he/she considers important in order to reduce the searching space. The authors have shown the convergent nature and validity of the obtained results. In the present study, however, users will have difficulty selecting among the positions of Spline node points, i.e., the design parameters, because the parameters cannot be isolated from each other in an aesthetic evaluation. This is true for many design objects. Establishing the relative importance among parameters based on the subject's selection record is thus likely to have applicational potential in many such cases.

We now discuss how the relative importance of feature parameters can be determined based on the user's subjective evaluation. Figure 8 shows the change in variances of different feature parameters over the generations. Figure 9 shows the change in the variance of evaluation scores. Decreasing variance of some parameter indicates that design samples having that parameter grow more uniform with each generation. Meanwhile, a decrease in the variance of the evaluation score means that the design samples produced are being evaluated similarly. Therefore, if the variances of a feature parameter and of the evaluation score both decrease, we may assume that the user regards the parameter as an evaluation criterion. If,

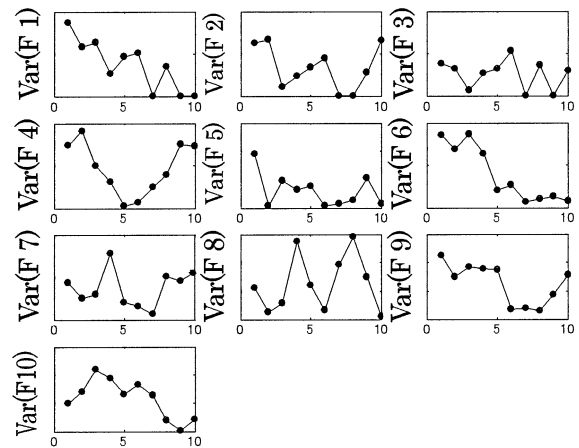


Fig. 8 Variance of feature parameters (Subject 1)

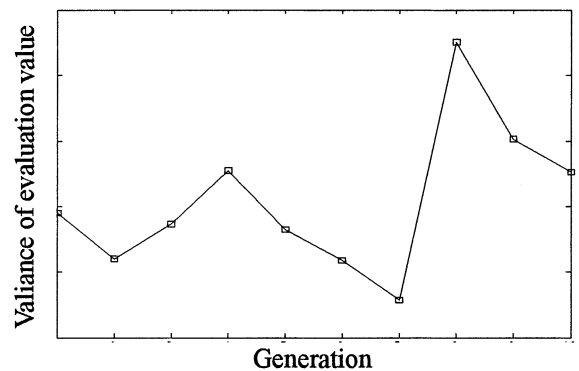


Fig. 9 Variance of evaluation value (Subject 1)

on the other hand, the variance of the evaluation score decreases while that of a feature parameter increases, then that parameter is not likely a factor in the evaluation process. These considerations then can be used as the criteria for establishing the relative importance among feature parameters. Quantification of the relative importance and its application to the system are subjects for future work.

4.4 'Rough' and 'detail' evaluations

In those generations displaying a divergent process, the design samples are heterogeneous and the user tends to evaluate roughly, i.e., from an overall impression. Conversely, in a convergent process, the presented design samples are similar to each other so that the user now examines the design details. When variations of a certain feature parameter exist within a single set (i.e., one generation) of samples, the design samples are heterogeneous with regard to that parameter. Conversely, if a feature parameter has a low variance within a set of samples, it is converging to a steady value.

Consider now a parameter which is considered important by the user. If the variances of that parameter and of the evaluation score both increase, we may assume that the user is 'roughly' evaluating that parameter. Or we can say that the parameter in question is being subjected to a 'rough evaluation'. Conversely, if the variation of the

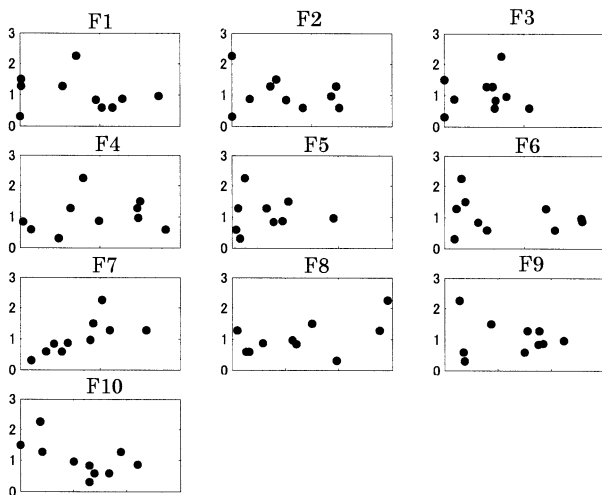


Fig. 10 Variance of evaluation value and feature parameters

evaluation scores increases while that of the parameter decreases, that parameter is being subjected to a 'detail evaluation'.

Figure 10 shows the relation between the variances of feature parameters and the variance of the evaluation score for subject 1. The vertical axis represents the variation of the evaluation scores while the horizontal axis shows that of the feature parameters. Here we can observe the relationship between a feature parameter and its relevance in the evaluation. For example, the variance of the 7th feature parameter (F7) increases as the variance of the evaluation score increases. In other words, this parameter is being subjected to a 'rough evaluation'. In the case of the 6th feature parameter (F6), the variance of the score is high when the variance of the parameter is low. It is thus being subjected to a 'detail' evaluation. In this manner, we can determine how much variation in a certain feature parameter will cause the user to change his/her evaluation.

By assigning relative importance (or weights) among feature parameters and determining whether they are being subjected to a 'rough' or 'detail' evaluation, it will be possible to track dynamic changes in the user's evaluation process, reduce the searching space and further improve the proposed method.

5. Conclusions

To meet the increasingly diversifying customers' requirements in product design, we proposed a support technology which allows the customer to participate in the industrial design process. Our interactive design support system for eyeglass frames was developed to satisfy customers who wish to design eyeglass frames on their own based on their individual tastes. Our method employs the Genetic Algorithm, using the user's subjective evaluation as the fitness value. The interaction between user and computer system converges to a satisfactory design by assisting the customer to produce a clear image of his/her

requirements.

The following results are obtained from experiments with non-designer subjects, and demonstrate the effectiveness of our system. Our developed system is shown to be effective for users who have a clear mental image of their design preferences, as indicated by the high correlation between the intensity (or clarity) of the mental image and the degree of satisfaction for the design result. The validity of the design results was verified by experimental results which compared pairs of 'satisfactory' and 'random' samples. Convergence of the solution toward the final generation was confirmed except for a small divergence in a near-final generation. This exception was considered due to the users' expectations for better results.

We examined the relative importance of features to users as well as the concepts of 'rough'/'detail' evaluations by analyzing the users' records of system operation.

As future topics, we plan to investigate methods of quantifying the relative importance of features and the 'roughness' of the evaluation, and incorporate the findings into a user's KANSEI (Sensitivity) evaluation method that can respond flexibly to various settings.

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