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PROPOSITION OF DISTINCTIVE INDUSTRIAL DESIGN BASED ON SHAPE AND COLOR FEATURE SPACE ANALYSIS

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Abstract

A computerized method of (a) calculating shape and color features of existing designs from their 3D polygon models, (b) analyzing the designs by representing them as vectors in a feature space, and (c) searching for a distinctive usage of shape and color as indicated by a vector furthermost from the existing vectors in the space, is proposed. In this method, the distinctiveness of a design from existing designs is mathematically defined and used in the search process. Such a solution should help a designer in creating a new design distinctive from existing ones, to attract consumer attention. The proposed method is implemented as software and applied to simplified models of nine personal computer designs and seven digital camera designs.

Keywords: Distinctiveness, 3D shape similarity, aesthetics design, optimization.

1. Introduction

In industrial design, a product's shape and color should meet the requirements of the desired function and usability and the targeted image and concept. In addition, testing a new shape and color different from those of existing designs is important for rendering the product sufficiently distinctive to attract consumer attention (Figure 1). To support the design of such distinctive products, we propose a computerized method of analyzing existing designs and searching for new usages of shape and color that differ as much as possible from existing designs.

Although industrial design is fundamentally performed on the basis of a designer's idea, numerous studies on computerized methods for supporting industrial design have recently been reported. Most of them, however, put emphasis on the determination of product shape, configuration and color to suit the targeted concept and image [1][2] or product functionality [3]; few studies have been reported on computational methods of searching for shape and color usages that are different from existing designs, as in the method proposed in this paper.

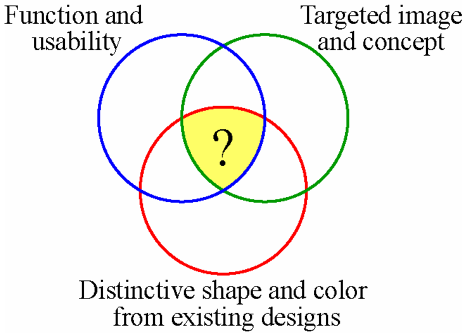


Figure 1. Candidate for distinctive design

2. Proposition of distinctive design by analyzing existing designs

2.1 Industrial design analysis/proposition based on shape and color feature space

In this research, we define features for quantitatively characterizing the shape and color of a design. By calculating the features of a design, the design is represented as a vector in a feature space (Figure 2: A two-dimensional space defined by only two features for clarity). In such a space, two close vectors may represent two similar designs because the vectors have similar usages for form and color. Figure 2 hypothetically explains an approach to design analysis/proposition as follows.

- Conventional personal computer designs have forms consisting of planes and low saturation colors (e.g., white, black, gray) which are plotted as vectors marked with × in the space.
- In such a situation, new designs with planar surfaces and low saturation colors marked with Δ should appear similar to existing designs.
- In contrast, new designs with curved surfaces and high saturation colors (e.g., blue, red, green) which are plotted as vectors marked with ○ should be appealing in terms of their newness and distinctiveness. Such newness and distinctiveness of the designs may quantitatively be indicated by the isolation and distance of the vector ○ from the existing vectors ×.

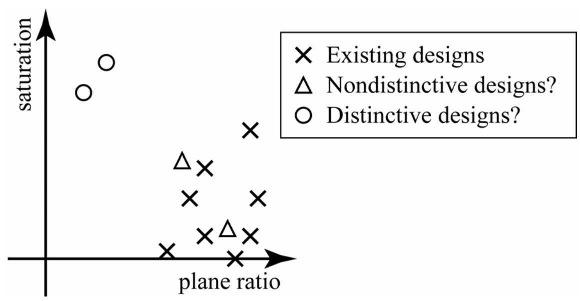


Figure 2. Industrial design analysis/proposition in feature space

Therefore, if we analyze existing designs and plot them in this space, we should be able to search for new and distinctive usages of shape and color as they will be indicated by vectors that are maximally isolated from the existing vectors. The aim of this research is to formalize the design activity hypothesized above as a method and technique, and implement them as software.

2.2 Analysis of industrial designs using 3D geometric model

In an initial rough design process for generating product shape and color candidates, some mathematical or systematic methods have already been utilized. Many of the methods, however, require complete or partial manual data processing. This might unconsciously introduce human preconceptions or stereotypes which might narrow the range of design possibilities. Also, when we use photographs and drawings of existing products for their analysis, such 2D information may not precisely or sufficiently convey the actual 3D characteristics of the designs and the analysis results might be inaccurate.

We propose an almost fully computerized method for analyzing existing designs and proposing distinctive designs using 3D model data of existing designs, to avoid the possible problems associated with conventional methods. Recently, products have been designed using 3D CAD/CG tools in many cases. Also, 3D shape and color information of products should be available in the form of digital data as a web catalog through the Internet, at present and in the future. Moreover, a 3D shape scanner is available for digitizing the shape and color of actual products if necessary. In such circumstances, it should not be difficult to collect the 3D shape and color data of products for these analyses.

2.3 Design representation with 3D polygon model

To carry out computational analysis, we require the 3D shape and color model of a product. We use a polygon model consisting of triangular facets for the following reasons:

- A polygon model can easily be obtained by transforming a 3D CAD/CG model, whereas the contrary is difficult in general.
- Even a polygon model consisting of planar triangular facets can represent a curved surface by specifying tangent continuity in facet connection.
- The output data from a 3D shape scanner is a polygon model in many cases.

Figure 3 shows the data structure of the 3D polygon model used in this research. To represent a product consisting of some parts as a polygon model, we introduce a "portion" to group vertices, edges and facets. Portions can share edges and vertices to form portion boundaries. Color information is assigned to each facet. The edges are categorized according to the following three types to represent curved surfaces with a polygon model in approximation: 'planar' (an edge between two facets constituting a planar surface), 'curved' (an edge between two facets constituting a curved surface) and 'edge' (an edge between two facets constituting a surface with a discontinuous tangent).

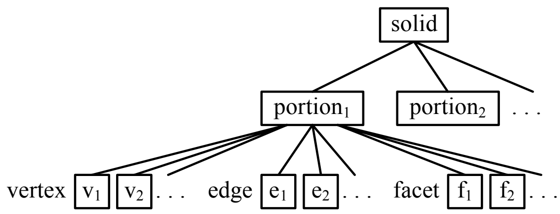


Figure 3. Data structure of 3D polygon model

3. Definitions of shape and color features

3.1 Shape features

To analyze designs from the viewpoint of form characteristics, we define the following shape features mathematically and implement their calculation for a polygon model. We manually specify the front and up directions of the polygon model which are necessary for defining some of the shape features.

There are some studies which define 3D shape similarity metric for retrieval, classification and recognition of 3D shapes. In those studies, they use mathematically general shape feature such as local curvature distribution of surfaces [4], shape histogram (shape existence distribution in shell/sector partitions of space) [5], a combination of the moment of inertia, the average distance of surface from the axis and the variance of distance of the surface from the axis [6], and shape distribution [7]. Since our purpose is to give designers hints on possible usages of shape and color features, we define and use such shape features that are comprehensive as possible design hints.

Filling ratio

Filling ratio of a 3D shape is defined by V/V_b, where V is the volume of a whole polygon model and V_b is the volume of its 3D bounding box. This feature takes a greater value for a lumplike shape and a smaller value for a shape with more irregularities.

Plane ratio

Plane ratio of a 3D shape is defined by S_p/S, where S is the total area of all facets and S_p is the total area of the facets representing the planar surface.

Height-to-width ratio

The height-to-width ratio of a 3D shape is defined using equation (1) where w and h are width and height, respectively, (viewed from the front) of the bounding box of the polygon model. According to the definition, this feature takes a positive value when w is greater than h, zero when w and h are equal, and negative when w is less than h.

$$\sin\left(\frac{w-h}{w+h}\cdot\frac{\pi}{2}\right) \tag{1}$$

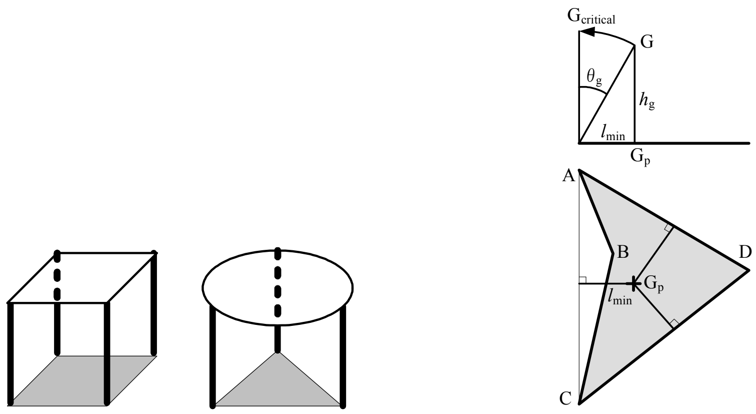
Simplicity

The simplicity of a 2D shape is defined by a dimensionless value A/l^2, where A is area and l is circumference length of the 2D shape [8]. Similarly, we define the simplicity of a 3D shape using equation (2), where V is the volume and S is the surface area of the entire shape. This value is 1 (maximum) when the shape is spherical.

$$6\sqrt{\pi}\cdot\frac{V}{S^{3/2}} \tag{2}$$

Stability (in relation to grounding area)

We quantify the apparent stability of a 3D shape in two ways. The first definition is based on the grounding area of the shape. We can consider a 2D convex hull formed with all grounding vertices of the 3D polygon shape. Similarly, we can consider a 2D convex hull formed with all the vertices of the entire 3D polygon shape projected to the ground. Here, we define the stability of the 3D shape by its grounding area which is defined by A_{ground}/A_{entire}, where A_{ground} and A_{entire} are the areas of the grounding and the entire projected convex hulls, respectively. Take the two chairlike shapes in Figure 4(a) as examples, although they are not polygon models. For a chair with a rectangular seat and four legs, both A_{ground} and A_{entire} are the areas of the gray rectangle in the figure, and thus the stability is 1 (maximum). For another chair with a circular seat and three legs, however, A_{ground} is the area of the gray triangle whereas A_{entire} is the area of the circular plate, and thus the stability is smaller than 1. According to the definition, the range of stability is between 0 and 1.



(a) Based on grounding area (b) Based on center-of-gravity position

Figure 4. Two definitions of 3D shape stability

Stability (in relation to center-of-gravity position)

The definition of stability above does not consider the position of the center of gravity. We define the stability of a 3D shape with respect to its center-of-gravity position as shown in Figure 4(b). In the figure, suppose G is the center of gravity, h_g is its height above the ground, $\mathrm{G_p}$ is its projected position on the ground, and ABCD is the grounding part of the 3D shape.

When we incline the 3D shape and move G to a position $\mathrm{G_{critical}}$ over an edge of the grounding convex hull, we can establish the shape as being in an unstable state (a critical state where the shape begins to collapse down spontaneously). The least value θ_g of such an angle is obtained when we incline the shape over an edge of the grounding convex hull closest to $\mathrm{G_p}$. A 3D shape with a greater θ_g is harder to render unstable and thus we define the stability of a 3D shape on the basis of θ_g $(=\arctan(l_{\min}/h_g))$ using formula (3). When θ_g is $\pi/2$, the 3D shape is most stable. When $\mathrm{G_p}$ is already outside the grounding convex hull, we regard $l_{\min}$ as negative which makes θ_g negative. Since the range of θ_g is from $-\pi/2$ to $\pi/2$, the range of the stability using formula (3) is from -1 to 1. The stability value is positive when a 3D shape is stable, zero when the shape is in a critical state, and negative when the shape is unstable.

$$\frac{2}{\pi}\arctan\left(\frac{l_{\min}}{h_g}\right) \tag{3}$$

We use these two definitions of stability (based on grounding area and based on the center-of-gravity position).

Horizontal symmetricity

We define a feature which takes a greater value when a shape is symmetrical in the horizontal (right-left) direction. We regard the center of gravity of a shape as a coordinate origin, and specify the forward direction of the shape as that along the x axis and the upward direction as that along the z axis. The x-z plane divides polygon vertices and facets into left and right side ones. When a projection $\boldsymbol{v}_{rc}$ of a right vertex $\boldsymbol{v}_r$ to the x-z plane is included by a projection f_{lc} of a left facet f_l to the x - z plane (Figure 5), we make a symmetric vertex $\boldsymbol{v}'_r$ of $\boldsymbol{v}_r$ for the x - z plane and an intersection $\boldsymbol{v}_{rf}$ of f_l and the line $\boldsymbol{v}_{rc}$ - $\boldsymbol{v}'_r$. Since $|\boldsymbol{v}'_r\ \boldsymbol{v}_{rf}|/|\boldsymbol{v}_r\ \boldsymbol{v}_{rc}|$ takes a small value when the shape is horizontally symmetrical at that position, we define the horizontal symmetricity by calculating the sum of that value for all of the right and left vertices using formula (4), where n_r and n_l are the numbers of the right and left vertices, respectively.

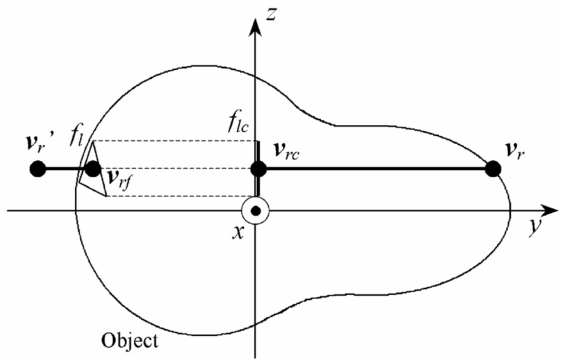


Figure 5. Horizontal symmetricity

$$\frac{1}{n_r + n_l}\left(\sum_{right}\left(1 - \frac{|\boldsymbol{v}_r'\boldsymbol{v}_{rf}|}{|\boldsymbol{v}_r\boldsymbol{v}_{rc}|}\right) + \sum_{left}\left(1 - \frac{|\boldsymbol{v}_l'\boldsymbol{v}_{lf}|}{|\boldsymbol{v}_l\boldsymbol{v}_{lc}|}\right)\right) \tag{4}$$

Vertical symmetricity

We define a feature to quantify symmetricity in the vertical (top-bottom) direction in a manner similar to the horizontal symmetricity, using the x - y plane instead of the x - z plane.

3.2 Color features

To analyze designs from the viewpoint of color characteristics, we define the following color features mathematically and implement their calculation for a polygon model. In this research, we quantitatively parameterize a color by hue, saturation, and lightness (value), for intuitive understanding. In an HSV (hue, saturation, value) color model, however, the human perception of colors is not quantitatively represented. For example, the degree of quantitative difference between two colors in an HSV color space does not indicate how different we humans sense the two colors. Therefore, we adopt the CIE Lab [9] color model in which a color is parameterized by the L value (a scale for lightness), a-value (a scale between red (+) and green (-)) and b-value (a scale between yellow (+) and blue (-)). In the CIE Lab color model, colors are parameterized in a manner in which human perception of colors is quantitatively represented.

Lightness mean, a-value mean and b-value mean

We quantify the mean of color lightness over the entire 3D shape. Since colors are assigned to facets of the polygon model, the feature is defined using formula (5), where L_i and S_i are the L value and area of a triangular facet i, respectively, and S is the surface area of the entire shape. The feature takes a greater value when brighter colors are used as a whole.

$$\sum_i \left(L_i \cdot \frac{S_i}{S} \right) \tag{5}$$

In the same manner and by using the a-value and b-value of a facet color instead of the L value, we define the means of the a-value and b-value over the entire 3D shape.

Saturation mean

In the CIE Lab color space, the saturation of a color is calculated as the distance between the point (a, b) of the color and the origin in the a-b coordinates. By using the calculated saturation value of a color instead of the L value in formula (5), we define the mean of the color saturation over the entire 3D shape. This feature takes a greater value when more vivid colors are used as a whole.

4. Search for distinctive design using optimization method

4.1 Definition of shape and color distinctiveness in feature space

In this research, we calculate the shape and color features for every existing design sample, plot every design as a vector in the feature space, and search for a new and distinctive design as a vacant space without any existing vectors nearby. To implement this concept as a computational procedure, we define a function to estimate the shape and color distinctiveness of a design, and search for a vector to maximize the function in the feature space using an optimization method.

To constitute a feature space using multiple features whose raw values differ in terms of their magnitudes and ranges, a normalized value x_n (between 0 and 1) is calculated for every feature by $x_n = (x - x_{\min})/(x_{\max} - x_{\min})$, where x, $x_{\min}$ and $x_{\max}$ are the raw value, theoretical minimum and maximum values of the feature, respectively.

When we use normalized N features (N-dimensional normalized feature space) for design analysis/proposition, I existing designs (as × marks in Figure 2) are represented as N-dimensional vectors $\boldsymbol{q}_i$ (i=1, 2, ... , I). To define an evaluation function to estimate the distinctiveness of an N-dimensional vector $\boldsymbol{p}$ against existing vectors $\boldsymbol{q}_i$ in this normalized feature space, the function should satisfy the following requirements.

- The function takes a greater value when less $\boldsymbol{q}_i$ exists near $\boldsymbol{p}$.
- The function takes a normalized value between 0 (minimum distinctiveness) and 1 (possible maximum distinctiveness) regardless of I (number of existing design samples) or N (number of features).

To meet these requirements, we define a distinctiveness function E using formula (6) to calculate for the mean distances between $\boldsymbol{p}$ and $\boldsymbol{q}_i$, and divide it by a maximum Euclid distance (between two diagonal corners) in the normalized N-dimensional feature space.

$$E(\boldsymbol{p}) = \frac{1}{I\sqrt{N}} \sum_{i=1}^{I} | \boldsymbol{p} - \boldsymbol{q}_i | \tag{6}$$

The purpose of most studies which define 3D shape similarity metrics [4][5][6][7] is to estimate similarity or dissimilarity between existing 3D shapes, whereas what we are doing in our research is to find possible usages of shape and color features to which no existing product shape corresponds.

4.2 Search for new and distinctive design

Now that we have defined a distinctiveness function E for an arbitrary vector $\boldsymbol{p}$, we can search for a possible distinctive design as a vector $\boldsymbol{p}$ which maximizes $E(\boldsymbol{p})$ in a normalized feature space using optimization methods. In this research, we use simulated annealing as an optimization method [10]. The search procedure using simulated annealing is described as follows.

(i) Determine an initial vector $\boldsymbol{p}_{current}$.

(ii) Determine the next vector $\boldsymbol{p}_{next}$ in the space at random.

(iii) Calculate the change of objective function $\Delta E(\boldsymbol{p}) = E(\boldsymbol{p}_{next}) - E(\boldsymbol{p}_{current})$.

(iv) If ΔE>0, keep $\boldsymbol{p}_{next}$ as a new current vector $\boldsymbol{p}_{current}$. If ΔE<=0, keep $\boldsymbol{p}_{next}$ as a new current vector $\boldsymbol{p}_{current}$ using the probability of $P = \exp(-\Delta E / aT)$, where a is the Boltzmann constant and T is temperature. Parameter T takes a high value at the beginning and gradually decreases with repetition of the procedure.

(v) If it reaches the termination criteria, end the procedure. Otherwise, return to (ii) to continue the procedure. An example of the termination criteria is that $\boldsymbol{p}_{current}$ does not move after a certain number of $\boldsymbol{p}_{next}$ candidates are tried.

A merit of using simulated annealing is that we do not require differentiation for the function E, and that we can possibly avoid being trapped in a local optimal solution by allowing a certain probability for vector movement even when ΔE<=0.

4.3 Feature space dimension for design analysis and proposition

When we have M features, we can conduct design analysis/proposition in M-dimensional feature space. In section 3, for example, we defined twelve features and thus M=12. Using numerous features for analysis/proposition [11], however, may result in the following problems.

- A proposed distinctive design based on a combination of values for numerous features may be difficult for a designer to recognize.
- Differentiating a design from existing ones by a combination of many features may be rather complicated and the resulting design may lack clear characteristics.

Using a small number of features for design analysis/proposition can possibly prevent these problems. Therefore, we adopt a strategy in which a designer specifies the number of features N for analysis/proposition among a number of defined features M (1<=N<=M). Since there are ${}_M\mathrm{C}_N$ combinations* for selecting N from M features, all of these combinations are examined in the design analysis/proposition as described in sections 6 and 7.

* ${}_M\mathrm{C}_N = \dfrac{M!}{N!(M-N)!}$

5. Software implementation

We implemented the design analysis/proposition method described above as a C++ program with OpenGL graphics. The operation procedure is described as follows (Figure 6).

(i) Load I 3D models of existing design samples (Wavefront "*.mtl" and "*.obj" files).

(ii) All defined M features are calculated for each of the I 3D models and saved in feature files. (Once the calculation is performed, the result can be read from the feature files.)

(iii) A designer specifies the number of features N for the design analysis/proposition.

(iv) I 3D models are plotted as vectors in the N-dimensional normalized feature space and a vector for maximizing the distinctiveness against the I vectors is searched for. Since the normalized feature space ranges from [0 0 ... 0] to [1 1 ... 1], the optimization by simulated annealing starts with an initial vector [1/2 1/2 ... 1/2] which is the middle point of the N-dimensional space. A found vector is saved as a possible distinctive design candidate in design proposition files. This design analysis/proposition is performed for every case of ${}_M C_N$ combinations. (Once this analysis/proposition is performed, the result can also be read from the design proposition files.)

(v) The distribution of the existing designs and the position of the proposed distinctive vector are displayed graphically.

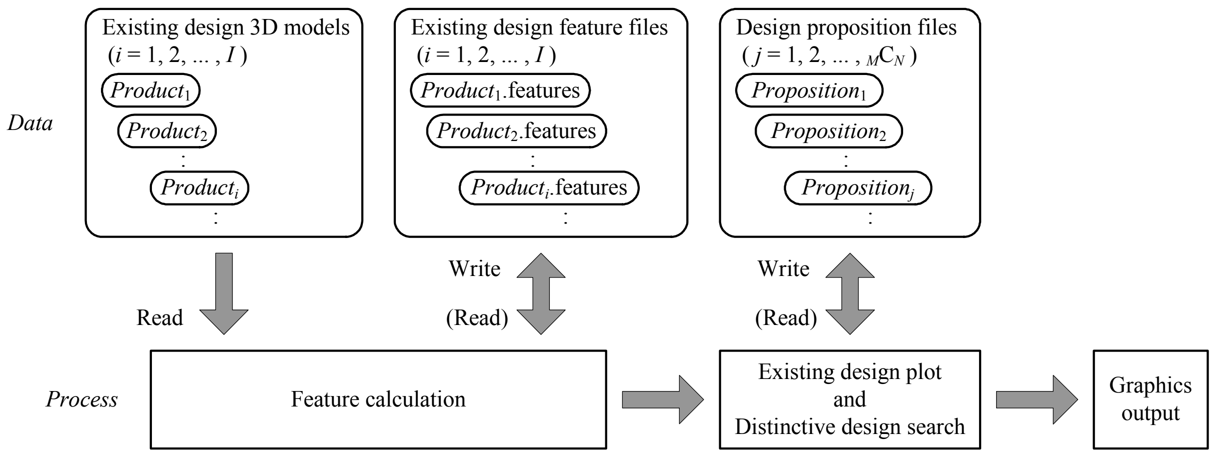


Figure 6. Process and data for design analysis and proposition

6. Example 1: personal computer designs

We applied our design analysis/proposition method and the implemented software to designs of two product categories**.

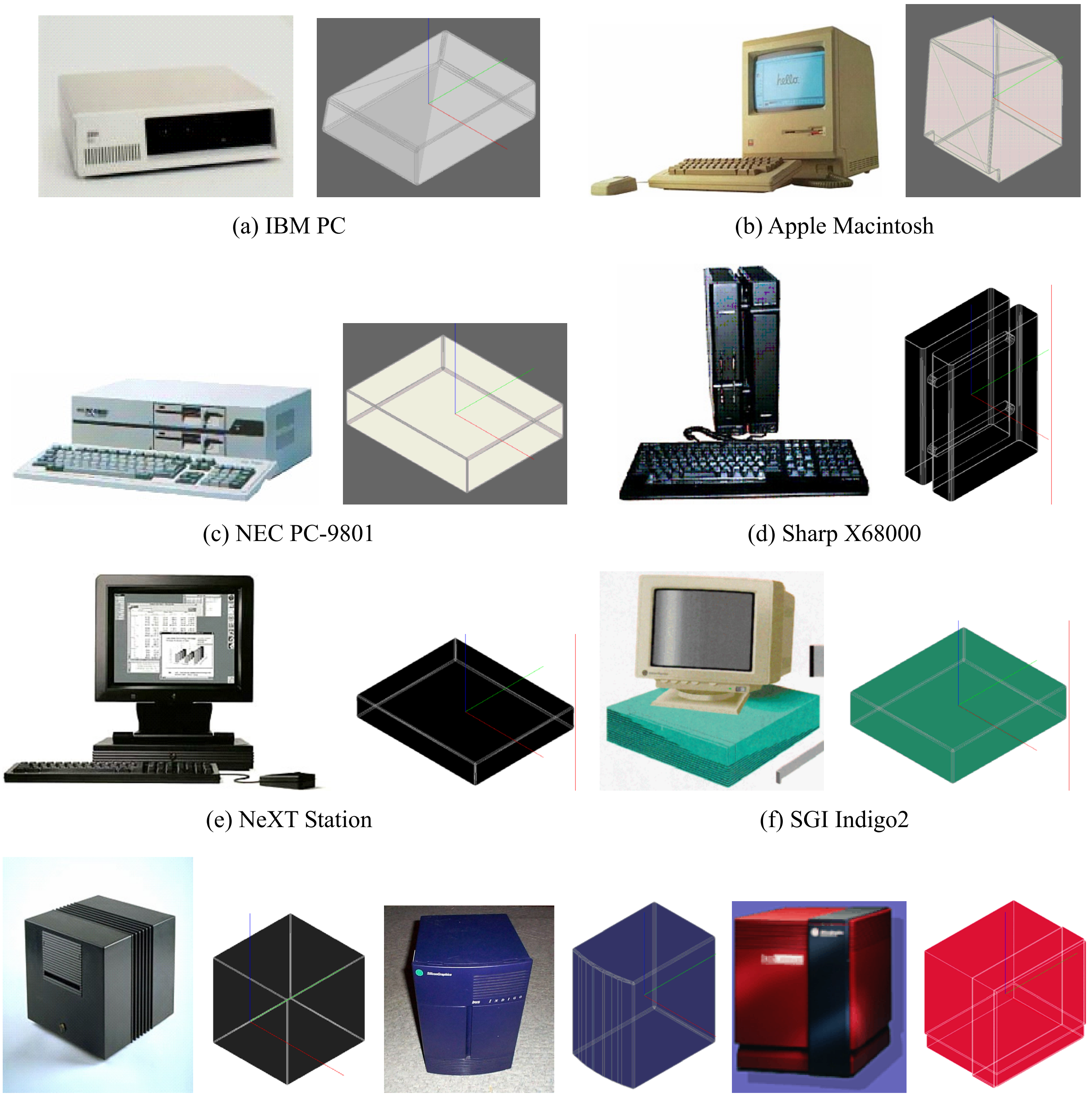
6.1 Design analysis and proposition

We selected nine samples (I =9) of personal computers (including some graphics workstations) and created their simplified 3D polygon models (Figure 7). First, all defined

** Note that we used the following product design examples simply to hypothetically confirm the validity and possibility of our proposed method, and none of the design examples, their design processes or their companies have anything to do with this research.

features (M=12) are calculated for each of the nine 3D models. Then we specified the number of features to be used as two (N=2) and conducted design analysis/proposition for every case of ${}_{12}C_2$=66 combinations.

Table 1 shows two examples from among all 66 considered distinctive designs: propositions of 6th-rank (with 6th greatest distinctiveness E) and of 57th-rank (with 57th greatest distinctiveness E). These analysis/proposition results provide a designer with two types of information as hints in considering a distinctive design, as follows.



(a) IBM PC

(b) Apple Macintosh

(c) NEC PC-9801

(d) Sharp X68000

(e) NeXT Station

(f) SGI Indigo2

(g) Next Cube

(h) SGI Indigo

(i) SGI Crimson

Figure 7. Nine examples of personal computer designs

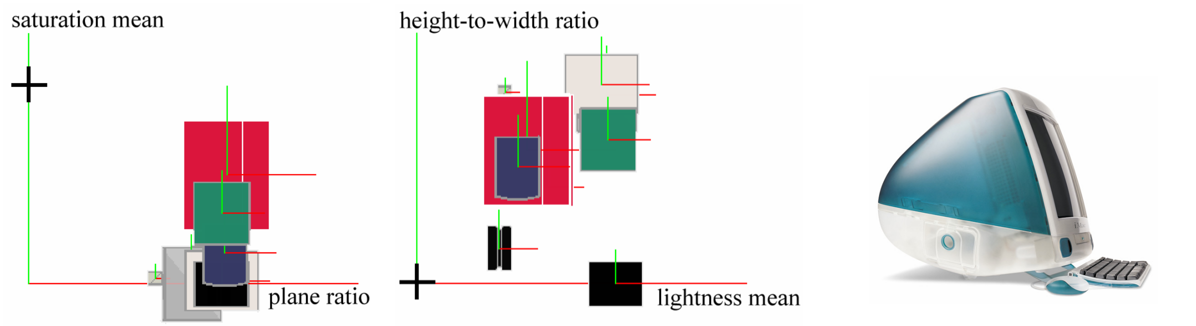
Table 1. Two Examples of Analysis/Proposition Results for Personal Computer Designs

Rank	Feature 1	Feature 2	Value 1	Value 2	Distinctiveness E
6	plane ratio	saturation mean	0.00205	0.994	0.907
57	height-to-width ratio	lightness mean	0.00305	0.00720	0.649

6.2 Hint on promising feature values for distinctive design

After designers have selected, decisively or on the basis of fixed assumptions, what shape/color features they will focus on when considering a new design, then they also need to consider how to use those features. Our design analysis/proposition results provide designers with hints for such considerations. Figure 8(a) and (b) show distributions of existing designs (3D models are drawn in plan view) and proposed distinctive solutions (marked as black +) in normalized feature spaces for the two analysis/proposition examples in Table 1.

Figure 8(a) indicates that if a new design is considered on the basis of a feature combination of plane ratio and saturation mean, a combination of a smaller value for plane ratio (shapes with curved surfaces) and a greater value for saturation mean (vivid colors) should make the design more distinctive from existing ones than other value combinations such as greater values both for plane ratio and saturation mean. Similarly, Figure 8(b) indicates that if a new design is considered on the basis of a feature combination of lightness mean and height-to-width ratio, smaller values for both lightness mean (meaning dark colors) and height-to-width ratio (meaning a thin shape in the vertical direction) should make the design distinctive from existing ones.



(a) Proposition of 6/66th rank (b) Proposition of 57/66th rank (c) Design example (Apple iMac) corresponding to proposition (a)

Figure 8. Two examples of design analysis/proposition based on nine personal computer designs

6.3 Hint on promising feature combinations for distinctive design

Before feature value consideration as in section 6.2, designers must consider what shape/color features they will focus on when considering a new design. Our design analysis/proposition results also provide designers with hints for such considerations.

When we consider distinctiveness E in Table 1, the 6th-ranked proposition (Figure 8(a)) achieves 0.907 whereas the 57th-ranked proposition (Figure 8(b)) achieves 0.649. This indicates that consideration of a new design based on a feature combination of plane ratio and saturation mean probably achieves greater distinctiveness than that based on a feature combination of height-to-width ratio and lightness mean. We can easily determine such an advantage by visually comparing the distributions of existing designs in Figure 8(a), with larger vacancy for a new and distinctive design, and in Figure 8(b), with smaller vacancy. This indicates that our design analysis/proposition method can create promising combinations of features among ${}_{M}\mathrm{C}_{N}$ combinations.

Among 66 propositions, we selected the 6th-ranked proposition (Figure 8(a)) as an example for discussion because it corresponds to the design of the iMac (Apple Computer Inc.) (Figure

8(c)). This indicates, although in a hypothetical and ex post facto manner, that solutions highly ranked with respect to distinctiveness E by our design analysis/proposition method of systematically examining combinatorial large number of possibilities can possibly include actual valid hints for a distinctive design.

7. Example 2: digital camera designs

7.1 Design analysis and proposition

Similarly as in section 6.1, we selected seven examples (I =7) of digital cameras and created their simplified 3D polygon models (Figure 9). Here, we specified the number of features to be used as three (N =3) and conducted design analysis/proposition for every case of ${}_{12}C_3$=220 combinations.

(a) Kyocera Finecam S31 (b) Konica Minolta DiMAGE X (c) Panasonic D-snap

(d) Panasonic Lumix FZ10 (e) Sony Cybershot F717

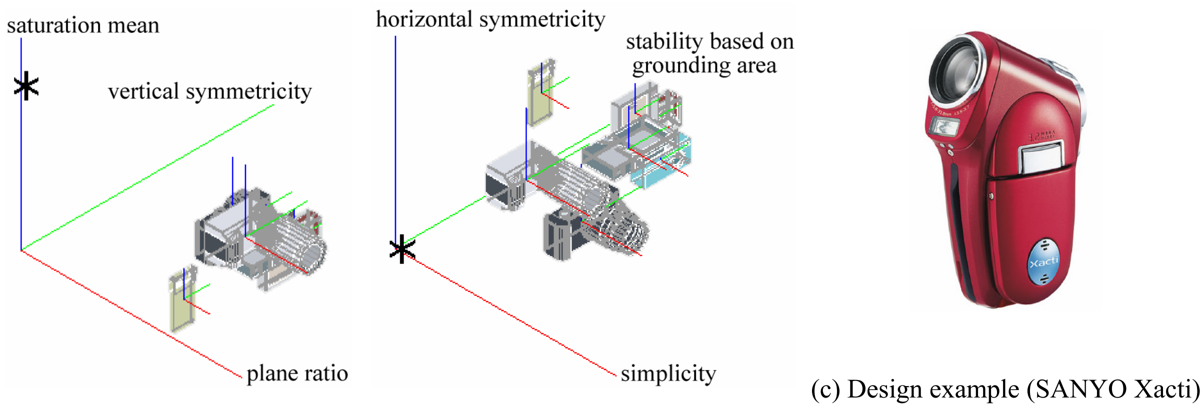
(f) Panasonic Lumix F1 (g) Ricoh Caplio RR1

Figure 9. Seven examples of digital camera designs

Table 2 shows two examples from among all 220 considered distinctive designs: propositions of 7th-rank (with 7th greatest distinctiveness E) and of 209th-rank (with 209th greatest distinctiveness E). Figure 10(a) and (b) show distributions of existing designs (3D models) and proposed distinctive solutions (marked as black +) in normalized feature spaces for the two analysis/proposition examples in Table 2. By comparing these two propositions, a designer should obtain the following hints.

Table 2. Two examples of analysis/proposition results for digital camera designs

Rank	Feature 1	Feature 2	Feature 3	Value 1	Value 2	Value 3	Distinctiveness E
7	plane ratio	vertical symmetricity	saturation mean	0.00922	0.0238	0.966	0.813
209	simplicity	stability based on grounding area	horizontal symmetricity	0.0202	0.0168	0.000824	0.550



(a) Proposition of 7/220th rank (b) Proposition of 209/220th rank (c) Design example (SANYO Xacti) corresponding to proposition (a)

Figure 10. Two examples of design analysis/proposition based on seven digital camera designs

7.2 Hint on promising feature combinations for distinctive design

Achieving distinctiveness seems more promising by considering a new design based on a 7th-ranked feature combination of plane ratio, vertical symmetricity and saturation mean than that based on a 209th-ranked combination of simplicity, stability based on grounding area and horizontal symmetricity. When we consider the existing design examples in Figure 9 after observing these two propositions, we notice that there certainly already exist both horizontally symmetric and nonsymmetric designs whereas most of them are vertically symmetric, and thus vertical asymmetricity can be more promising for distinctiveness than horizontal asymmetricity.

7.3 Hint on promising feature values for distinctive design

The 7th-ranked proposition indicates that if a new design is considered on the basis of a feature combination of plane ratio, vertical symmetricity and saturation mean, a combination of smaller values for plane ratio (shapes with curved surfaces) and vertical symmetricity (vertically asymmetric shape) and a greater value for saturation mean (vivid colors) should make the design more distinctive.

We selected this 7th-ranked proposition (Figure 10(a)) as an explanation example because it corresponds to the design of a recently released actual product (Figure 10(c)). This indicates, although in a hypothetical and ex post facto manner, that solutions highly ranked by our design analysis/proposition method can possibly suggest an actual valid hint for a distinctive design.

8. Discussion

The design analysis/proposition method described in this paper is based only on objective information for 3D models and considers only "shape and color distinctiveness" condition as depicted in Figure 1. Whether the proposed hints can be good designs or not is still up to designers' judgment. Also, possibly subjective issues such as relationships between aesthetic attributes and human perception [12] or consumer tastes for product shape and color are intentionally excluded. Such subjective issues in industrial design may be considered in the following ways:

- They are expected to be subject to large variability, or sometimes even complete difference, according to individual preferences.
- They are expected to change with time or fashion.
- They should not be an unconditional precondition for design processes, but rather, some revolutionary design should be able to change them.

Such premises should indicate that clearly separating subjective and objective issues into two distinctive layers may lead to the development of a clear, robust and maintainable design method and its software implementation. In this sense, the author considers that the exclusion of subjective variables can be considered a merit of our approach at present. Adding a "subjective issues" layer on the current "objective issue" layer should be our next step.

9. Conclusions

(1) A computerized method for calculating shape and color features of existing designs from their 3D polygon models and analyzing the distribution of the designs by representing them as vectors in a feature space is proposed.

(2) A mathematical definition of shape and color distinctiveness from existing designs based on normalized feature space analysis is proposed.

(3) A computerized method of searching for distinctive usages of shape and color as vectors for maximizing the distinctiveness function in the normalized feature space using an optimization technique is proposed.

(4) The proposed method is implemented as software and applied to the design analysis/proposition of personal computer designs and digital camera designs. It is confirmed that the proposed method and software can indicate some valid hints for the development of distinctive designs.

This research is at an initial stage, and much work needs to be carried out to establish a practically effective design analysis/proposition method and computer software as follows.

- Currently, we define shape and color features which are mathematically clear and easily implemented in software for 3D polygon models. We need, however, to consider what shape and color features are necessary or effective in order to discuss real design issues and implement them as software.
- A real product, in general, consists of multiple parts which can have similar or different shape/color features. Without considering the relationships among features of the parts, we cannot discuss design issues such as "balance", "accent" and "unity/variety" [13].
- Although we have already obtained some comments from industrial designers, we need to confirm the validity of the method and software through a real product design process.

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