ORIGINAL ARTICLES

SYSTEMATIC CONSTRUCTION OF SHAPE GRAMMARS FOR THE FORM DESIGN OF THE PRODUCTS

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Abstract: Shape grammars have been developed from the analyses and creative designs of architecture forms to generate the product forms as a computational method recently. All the shape grammars presented in the literature lack explanation about how they were constructed. So trying to create the shape grammar for product becomes very challenging, since it is difficult to induce rules from thousands of models of a particular product without any guidance. The objective of the paper is to propose a systematic approach which enables us to construct the shape grammar for the form of a particular type of a product. A scooter case study illustrates the proposed process for constructing the shape grammar of products.

Keywords: *Shape Grammar, Scooter, Systematic Construction, Form Design*

1. INTRODUCTION

The shape grammars originated from architecture as an expression tool for the form analysis of buildings and as an inference mechanism for the generative design with a similar architectural style [1-5]. Shape grammars as an architectural form language consist of a set of shape vocabulary and syntax rules. The architect's style can be studied by the shape grammars.

In recent years, shape grammars have been extensionally applied to the analysis and design of product forms ranging from coffee makers to automobile inner hoods [6, 7]. In fact, architecture and industrial design share a lot in common, including vocabulary, syntax, semantics, and styles. They both have similar concepts in the study of spatial relationship, the abstraction of forms, the dialogue of functions and forms, and the rules of generative design. The logical and rational reasoning about the product forms can be also stated in the shape grammars. They can be used as a basic guideline to assist the designers generating creative forms along with their emotional feeling, experience, and intuition. Furthermore, the design of product forms based on shape grammars was associated with the brand and product identity [8-10]. Hsiao, S.W. et. al. pioneered to propose a semantic and shape grammar based approach for product design [11]. In his works, the adjective image words were expressed and evaluated for perception of product/brand identity. Then the product forms were correlated to the image words by several methods such as fuzzy set and multi-dimensional scaling. Next, the constitutional components of the products were identified, and their corresponding shapes were categorized. Finally, the shape regulating rules were used to generate various forms. Another direction of developing

the shape grammars was studying the consistency between the product form and its brand/product identity. The relationship of product form and product identity was established first. Then the rules of the relationship as constraints were defined in a shape grammar. Completely new forms could be created by loosening the constraints until the product identity disappeared, thus a brand new product in turn appears.

While shape grammars are used to create the shape of a product, the relationship of layout, functions, aesthetics, ergonomics and shape should be considered simultaneously. For a typical complex product or architecture, a shape grammar may comprise tens or hundreds of rules due to many elements and connections of elements. It becomes evident that a systematic construction of shape grammar is needed rather than a intuitive trial and error. The validity of shape grammar is not confined due to a complex product like a scooter. On the other hand, the other traditional shape-creating methods such as analogy thinking, image map inspire the designers creating new shapes in a black box. Apparently shape grammars provide the insight of innovative shape creating for the designers.

Shape grammars for products can be created with different purposes. Furthermore, the process of creating shape grammars is ambiguous in the literature. It is very difficult to construct the shape grammar of products with complex compositions, because one must rely on experience and trial-and-error. The systematic generation of the shape grammars for products has not yet been studied and explicitly expressed. In this paper, scenarios of constructing shape grammars are discussed. Then the framework of constructing shape grammar is developed for various scenarios. A scooter case study illustrates the systematic construction of a shape grammar.

2. FORMULATION OF THE SHAPE GRAMMAR

To develop shape grammars for products, the shape grammar formalism is introduced first. According to Stiny, G. [2], the shape grammar $G = (S, L, R, I)$ consists of four components:

- (1) S is a finite set of shapes,
- (2) L is a finite set of labels,
- (3) R is a finite set of shape rules of the form $\alpha \rightarrow \beta$ where α is a labeled shape in $(S, R)^+$, and β is labeled shape in $(S, R)^*$.
- (4) I is a label shape in $(S, R)^+$ called the initial shape.

S is the set of primitives such as point, line, plane, or solid, circle, or rectangle which are used to construct the shape of the object. The label in L orients the operation of rule like the base line or the grid on the background to assist the shape construction. The rule in R is the transformation of the label shape α to the labeled shape β . The arrow $\rightarrow$ means a shape transformation. For example,

, α - a rectangle with a dot label - rotating 45 degrees around its center and shrinking the length of edge becomes a labeled diamond-shape - β . The dot label $\bullet$ orients the shape of rectangle and diamond. Without the dot label, the rectangular and diamond shapes are equivalent with respect to the rotation. $(S, R)^+$ and $(S, R)^*$ represent the sets of left-side and right-side label shapes respectively.

Figure 1 illustrates the simple shape grammar to create the designed shape by applying Rule 1 twice and Rule 2 once consecutively. Rule 2 is a terminal rule to remove the dot label.

3. SYSTEMATIC CONSTRUCTION OF THE SHAPE GRAMMAR

The shape grammars for creating product forms can be used in different situations. From the literature, the scenarios of constructing the shape grammar for product forms can be categorized as follows:

1. Redesign and create the new product forms for an existing product model to retain the consistency of

- brand/product identity, or to predict the product image.
2. Create the new product forms for the brand/product images.
3. Analyze and explore key product features from comparison with competitors.

The ways of constructing the shape grammar were ambiguously described. This paper proposes a systematic process to assist the designers constructing the shape grammar. The process of constructing shape grammars includes the following steps:

- A: Decision of the subject and product samples,
- B: Identification of key design elements,
- C: Defining of the joining relationship,
- D: Defining of the shape of the key design elements,
- E: Defining of the shape relationship of the key design elements,
- F: Representation of rules in shape grammar formalism,
- G: Examination of shape grammar from product samples.

The proposed process can be applied to all the above mentioned scenarios. The major difference of constructing shape grammars in different scenarios is selecting the product sample. The detail of the process is discussed and illustrated with a scooter case in the following sections.

3.1 Step A: decision of the subject and product samples

The subject for the form analysis is determined first. Since the original subject was invented, a diversity of product models in the subject have been developed to reflect the advance of technology, aesthetical preference, and living style in its era. The product family of the subject usually becomes huge while the subject evolves with time. The samples for form analysis can be selected from the product family according to our interest. Three factors are considered when it comes to selecting product samples in various scenarios: timeline, company, and model type. The selection requirements of product samples for different scenarios are described in Table 1. The product models from color variation, and add-in decorating parts are not considered in this paper. Thus, the product samples can be selected from the huge product family. Next, information of the products samples can be collected from web sites, books, magazines, catalogs, and design patents. The information includes

Table 1: The selection requirements of product samples for different scenarios

Scenario	Selection requirement of product samples
1	Samples in one model type within one company through historical timeline.
2	Samples in all model types within one company through historical timeline.
3	Samples in one or several model types in current market across the whole industry.

Figure 1: A simple shape grammar

figures and specifications. In this stage, the knowledge of the subject and the product models must be built. It will be used to determine the key design elements and specify the parameterization of the element shapes. In this paper, scenario 3 is selected to illustrate our approach. The subject is a scooter. The information of the 50 c.c. scooter models is collected from the product catalogs, web sites, and magazines.

3.2 Step B: identification of key design elements

The key design elements play an important role in the expression of product form. The key design elements in form analysis can be determined by the following factors:

- (1) the elements are visible,
- (2) the elements are critical in visual expression,
- (3) the detail level of form analysis.

Practically the industrial designers decide the key design elements which appeal customers' interest from first look. The shape grammar constructors consider the above viewpoint to identify the key design element from product samples as shown in Figure 2 [12-14]. The identification of key design element starts from comparing the user interface and covers of the mechanical and electronic parts from all product samples. The most common elements are

Figure 2: Product samples of the scooter

a. Instrument console	j. Side cover
b. Headlight	k. Center cover
c. Front cover	l. Seat
d. Front turning signal	m. Rear fender
e. Front fender	n. Body cover
f. Front wheel	o. Taillight
g. Handle bar	p. Rear turning signal
h. Inner cover	q. Rear wheel
i. Footrest panel	

Figure 3: The key design elements of the scooter

selected and the others are determined by the detail level of form analysis. The key design elements of the scooter are shown in Figure 3. In the scooter case, the gas tank is ignored due to invisibility. The key hole is not considered as a critical visual element and the brake disk of wheel is skipped for its detail expression in preliminary design.

3.3 Step C: defining of joining relationship

As the architect Sullivan's famous dictum has it: "Form follows function". The product functions are considered first for extracting the form features of the product. Then the shape grammar rules can generate the product forms that are feasible in the physical world. The product functions affect the key design elements in three ways: the joining relationship, the shape relationship, and the shapes of the elements.

The extraction of form characteristics is performed in Steps C, D, and E. In current step, the joining relationship is investigated by the following procedures. The joining relationship of elements in a product can not be arbitrary from the consideration of functions. For example, a headlight is impossibly connected to a wheel, but it is possibly on the front cover. The designers observe the product samples and decide the correct join relationship among elements. First, the reference elements such as a coordinate system and the boundary lines must be determined first. They provide a fundamental viewpoint for studying the joining relationship of the design elements. The coordinate system can be decided by the preference of the industrial designer. The boundary lines such as length, width and height are given from technical specification and customer requirements. The boundary lines can be also from the ergonomic requirements. Additional, the industrial designer usually starts designing a product outlook from the naked mechanical framework with electronic and mechanical parts. The reference line should be extracted from naked mechanical framework. In the scooter case, the reference geometric object is the naked body frame. The ground line and the wheelbase lines which are traditional specification of a scooter are defined as boundary lines. The human posture for riding is also considered as boundary lines before the industrial designer can design the shape of component for the rider interface.

Second, the product should be virtually segmented into several portions. The same portion of different product

Figure 4: A morphological chart of front fender

samples can be mapped into a morphological chart for investigating the joining relationship among components. Figure 4 shows a morphological chart for scooters [12-14]. For example, it can be easily found that the front fender is attached in the front fork or the front cover. Figure 5 describes the joining relationship of components from the direct observation. It is suggested that the description of the spatial relations starts from the global structures to detail attachments. The spatial relationship determined the sequence of the rule application in shape grammar.

3.4 Step D: defining of shapes of the key design elements

While designing the shape of three-dimensional components, they can be represented by several methods: wire frame, three two-dimensional views (front, side, and top views), a family of cross-section curves, and single 2-D profile. The selected representation methods should be able to clearly represent the shape of the component in shape grammar formalism. The selection of the representation methods will not affect the effectiveness of the constructing shape grammar process. In the case study, the form of the scooter is represented by a 2-D side-view profile. The shape of each component is represented by connecting line segments as its boundary line.

After the selection of the representation methods, the ergonomics and functional requirements should be considered while designing the shapes of the key appearance components. For example, the human factors constrain the shape of the seat and the size of the front cover should be large enough to cover the front fork and attach the headlight. The shape grammar will not be able to generate exactly the same product sample without parameterization of the characteristic shape of the design elements. In the scooter case study, the shape represented in shape grammar without parameterization is sufficient for the form studying of scooters.

3.5 Step E: defining of shape relationship of key design elements

Defining the shape relationship of key design elements imposes the constraints on shape design of each element.

The instrument console a is connected the front fork.
The instrument console a is connected to the handle bar g.
The instrument console a is connected to the inner cover h.
The headlight b is on the front cover c.
The headlight b is connected to the front turning signal d.
The front cover c is connected to front fork.
The front cover c is cover the handle bar g.

Figure 5: The description of the spatial relationship of the key design elements

The constraints can be categorized as three groups (1) geometric interference, (2) shape matching, and (3) consistent style. All the design rules from the shape relationship among the key design elements should be described in this step. The constraints will be used to check the validity of the shape grammar rules.

First, each component should not interface with each other when they are assembled in space. Figure 6 shows an invalid rule, because the shape k interferes the shape j. Thus the shape k or the shape j should be redesigned. Exceptional case is that the shape of the components is represented in term of shape grammar in 2D view. For example, the front fender can be fit into the cavity of the front cover while they are represented in 2D shape grammar as shown in the Figure 7, but they do not interference with each other.

Second, the shapes among the objects should be matched in terms of engineering functions. For example, the rectangular axis will not fit into the circular hole.

Third, the style of the key appearance design components should be consistent. For example, the round and cute front-cover style should be consistent with the body cover style. Otherwise, the different vocabulary of the key design elements could cause awkward forms. The shapes of the key appearance design components should be checked by this principle.

3.6 Step F: representation of rules in shape grammar formalism

After enough data has been collected, the shape grammar can be constructed. Although the sequence of constructing the rules will not affect the application of the shape grammar, it is suggested that the shape grammar is constructed in a systematic way for avoiding errors. The steps for constructing the rules are described as follows:

(1) Rules for the reference elements: the information is gathered in Step D,

Figure 6: Inappropriate composition of the shapes

Figure 7: Appropriate composition of the shapes

- (2) Rules for creating key design elements: the information is gathered in Steps C, D and E.
- (3) Rules for termination: removal of reference elements and labels.

The rules for the scooter should include the following groups:

- (1) Rules for the reference geometric objects: the reference object including the position of axles, ground clearance, and the human posture.
- (2) Rules for generating key design elements of the scooter: the key design elements as listed in Figure 3 are generated.
- (3) Termination: removal of the labels and references.

Figures 8 – 12 shows the scooter shape grammar. Each rule is explained in the following:

Group (1)

Rule 1: The initial shape is a point with a label O at the origin of the coordinate system. Define the original point as the axle center of the rear wheel.

Rule 2: the axial position of the front wheel is defined by the wheelbase length.

Rule 3: the bottom boundary line is created for ground clearance.

Rule 4: the footrest line is created.

Figure 8: Rules 1 – 8 in a scooter shape grammar

Rule 5: the length and rake angle of the front fork is specified.

Rule 6: the profile of the body frame is added.

Rule 7: the swing arm is connected to the body frame.

Rule 8: the foot of seated human is on the footrest line.

Group 2:

Rule 9: the wheels are added.

Rules 10 – 11: Either Rules 10 or 11 are applied to add

Figure 9: Rules 9 – 17 in a scooter shape grammar

the straight or Y-shape handle bar. The position of the hands and the front fork constrains the selection of rules. Rules 12 – 13: If the Rule 10 is selected, Rule 12 should be followed to add the instrument console; otherwise, the Rule 13 should be applied.

Rules 14 – 16: One of the rules should be applied to attach the front cover.

Rule 17: There is no front cover.

Figure 10: Rules 18 – 27 in a scooter shape grammar

Rules 18 – 20: The inner cover should cover the front fork partially and match with the shape of the front cover. One of the rules is selectively applied to add the inner cover.

Rule 21 – 22: Two types of front fenders can be selected

Rule 23: There is no front fender. The front cover works as the function of the front fender.

Rule 24: the side cover is attached to the front cover side by side.

Rule 25: the center cover is located above the side cover.

Rule 26: the body cover is connected to the side cover and the center cover.

Rule 27: there are no side cover, center cover, and body cover.

Rule 28: the seat is added.

Rule 29: the footrest panel is created.

Rule 30: the headlight is on the front cover.

Rule 31: the front turning signal is on the front cover, but it is not integrated with the headlight.

Rule 32: the integral set of headlight and front turning signal is on the front cover.

Rule 33: the rear fender is created.

Rule 34: the taillight is created.

Rule 35: the rear turning signal is created.

Rule 36: the integral set of taillight and rear turning signal is attached on the body cover.

Figure 11: Rules 28 – 32 in a scooter shape grammar

Rule 37: the integral set of taillight and rear turning signal is attached on the seat.

Group 3

Rule 38: the labels are removed.

Rule 39: the reference objects are removed.

3.7 Step G: examination of shape grammar from product samples.

Now we use our shape grammar to generate different forms of scooters. The appropriate order of applying the rules in shape grammar to form the scooter is shown in Figure 13. Four cases are used to investigate the validity of the scooter shape grammar.

Case 1: The sequence of rule application is the rules 1-9, 10, 12, 14, 18, 21, 24, 25, 26, 28, 29, 30, 31, 33,

Figure 12: Rules 33 – 39 in a scooter shape grammar

34, 35, 38, and 39. The generated shape is shown in Figure 3

Case 2: The sequence of rule application is the rules 1-9, 11, 13, 15, 19, 21, 24, 25, 26, 28, 29, 30, 31, 33, 36, 38 shape grammars to form the scooter.

and 39. The generated shape is shown in Figure 14.

Case 3: The sequence of rule application is the rules 1-9, 11, 13, 14, 18, 22, 24, 25, 26, 28, 29, 30, 31, 33, 36, 38 and 39. The generated shape is shown in Figure 15.

Case 4: The sequence of rule application is the rules 1-9, 10, 12, 16, 20, 27, 28, 29, 30, 31, 33, 37, 38 and 39. The generated shape is shown in Figure 16.

The shape grammar is validated for creating scooter shapes from four cases.

Shape grammars are a set of rules which can create various forms. This paper only shows three examples of applying the rules in shape grammar for explanation. More various product forms can be created by different ways of applying the rules. Before applying a shape grammar, a shape grammar should be validated by regenerating the known product form for avoiding invalid product forms. The rules in shape grammar can not be contradictory. Creating shape grammars of products is tedious, but it is convenient and easy for regenerating new shapes of products.

Figure 13: Appropriate order of applying the rules in shape grammar to form the scooter

4. CONCLUSIONS

Shape grammars extract and express explicitly the complicated forms of products in simple rules. Without the assistance of shape grammars, designers extract and reason the design principles for forms of products in their own experiences after long practice. Shape grammars like a rule-base knowledge base assist designers regenerating the reasonable forms of products and allow designers creating product forms in their own styles. Furthermore, the shapes of product samples could be possibly regenerated by different shape grammars from different designers and the construction process is quite difficult for beginners. Thus the systematic construction of the shape grammars for products is proposed in this paper. The constructing process contains seven steps from sample selection, defining the key design elements and their joining relationship, and shape relationship to the representation

Figure 14: The generated scooter shape in Case 2

Figure 15: The generated scooter shape in Case 3

Figure 16: The generated scooter shape in Case 4

and examination of shape grammar rules. The proposed method cannot totally replace the subjective thinking of the designers. The step-by-step guide in this method can assist designers creating a feasible shape grammar efficiently. The applications of constructed shape grammars for designing product forms can be accelerated. A Taiwan-based motorcycle company adopts authors' proposed method. The result shows the significant improvement of the designers' productivity.

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