COMPUTABLE FEATURE-BASED QUALITATIVE MODELING OF SHAPE

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Abstract.

This paper introduces and describes a qualitative approach to the modeling of shapes applicable at the early stage of designing. The approach is based on using qualitative codes at landmarks to describe shapes. These strings of codes can be analysed to determine patterns which map onto features. An analogy with language is drawn to assist in articulating the modeling ideas. An example is presented which demonstrates the utility of the approach.

1. Introduction

In modeling architectural designs, it is usual to consider shape and space as two fundamental primitives. Designers as well as researchers have an increasing concern about how to handle these primitives better through the development of better design descriptions that are more appropriate to the design situation than current description techniques. There has been considerable success in modeling architectural designs using quantitative approaches. For example, CAD package which are nowadays often synonymous with drafting programs, are based on quantitative descriptions of shapes, ie., those descriptions requiring all the necessary detailed measurements sufficient to display the designed object on the computer screen. Unfortunately, those detailed measurements are only available at the final stages of designing. Therefore, modeling of designed objects is not readily available during the early or conceptual stage of designing because of the unavailability of the numerical data. In order to fully utilise the power of computational support tools, it should be possible to have design aids from the early stages of the design process regardless of the accuracy of the available design information. This leads us away from numerical descriptions to symbolic descriptions which represent qualities rather than quantities. It is proposed that shapes can be represented through a range of qualities which are available at the early stages of designing. The ability to represent shape qualities provides opportunities to link such shape qualities to space qualities since it is the space which is being designed with the shapes a consequence.

Qualitative approaches based on symbolic modeling provide different viewpoints in the sense that no accurate measurement of shape or space is needed to model the design primitives. There have been a number of symbolic schemes developed to handle shape and space. One of the most common approaches to handling shapes is based on contour lines of the shape which are de-segmented using directional vectors (Freeman 1961, Weinberg et al 1992, Jungert 1993). Most symbol systems for modeling space are concerned with capturing spatial relationships such as topological relations (Clarke 1981, Egenhofer and Al-Taha 1992, Randell et al 1992) or orientation relations (Allen 1983, Chang et al 1987) among spatial objects. Nevertheless, these symbolic modeling schemes display restrictions and limitations when applied to architectural shape and space since little effort is given to understanding the correspondence among shape characteristics, design semantics, and spatial characteristics of designed objects. Therefore, a more suitable and flexible symbolic scheme is needed in order to overcome the limitations of currently available symbol systems.

In this paper we demonstrate a qualitative modeling scheme for handling shape based on descriptions of the shape features. We will leave for another paper the issue of modeling space qualitatively and how to link the modeling of shape with that of space.

2. Methods

Here we use concepts derived from feature-based modeling to capture design knowledge related to the qualitative character of shapes. This will be presented in three steps. The first step is to develop an appropriate representation scheme: this is based on previous work on syntactic pattern and contour representation methods (Freeman 1961, Fu 1976), with which we can describe distinctive shape characteristics of drawings. The second step is to turn those qualitative descriptions of shape into a meaningful shape semantics. The third step is to discover meaningful shape, and then later design, semantics by using syntactic pattern matching of features from the given description of shape. Although the syntactic approach to the representation is not new, our syntactic representation scheme for qualitative characteristics of shape extends current generic methods and specialises them for design-related tasks which have previously either been unavailable or have been difficult.

2.1. Q-CODE REPRESENTATION OF SHAPE

Humans seem to recognise and identify complex forms by registering their characteristic features and their peculiar configurations (Treisman and Gelade 1980). Drawing, which is a fundamental tool for designers to express and communicate design ideas to others, is concerned with forms and figures which are entities made up of shapes. A shape is taken to be a finite arrangement of lines (straight, curved, open or closed) in the plane drawn in a finite area in a finite amount of time (Stiny 1978). The shapes we are concerned with are made of closed and connected lines, which define a boundary contour of a spatial object.

The qualitative representation of drawings looks for general features with which we could distinguish one drawing from another. The term “feature” refers to any geometric and topological entity (Shah 1991), or just a named entity with attributes of both form and function (Stiny 1989). The basic features that capture the physicality of a shape are mostly “the shape attributes” with characteristic variable names and values. We therefore use shape features to encapsulate design significances and to associate them with their geometry, functionality and design semantics.

2.1.1. *Encodings formalism*

Setting qualitative values to shape attributes follows a strict formalism suggested by researchers from the qualitative reasoning community (deKleer and Brown 1984). Qualitative values are set to variables by mapping their numeric values (where they exist) to a finite and discrete set of symbolic values. Where the numeric information does not exist, a lexigraphic ordering of the concepts can be used. The simplest way of setting qualitative values from the real number range of values is to use a “landmark set” with qualitative values in the range {-Ï, 0, Ï}. Then the set of intervals becomes {(-Ï, 0), [0, 0], (0, Ï)}, which corresponds to the qualitative set Q with the sign values {+, 0, -} (Wertner 1994). This simple yet effective process of symbolic mapping is useful in modeling design variables and attributes, transforming possible numeric value ranges into small sets of discrete and finite symbol values. This formalism of setting qualitative values can be applied to most design variables since most values can be measured in terms of “polarity” and “granularity”.

2.1.2. *Shape-attributes and Q-codes*

Q-codes are formulated by combining symbols with sign values. Four types of shape attributes are considered to be fundamental in describing shapes in this qualitative way. These are:

(i) angle measured at a node, A-code;
(ii) relative length of line segments, L-code;
(iii) angle measured at a node for two tangents, C-code;
(iv) relative curvature of a line segment, K-code

Q-codes in (i) and (ii) are basic shape attributes necessary to describe arbitrary polygonal shapes, while Q-codes in (iii) and (iv) are needed to describe arbitrary curvilinear shapes. Symbols stand for categories of shape attributes and sign values stand for their qualitative values.

The A-code describes the qualitative measure for the inner angle at a node between two contiguous line segments in a shape. The C-code is a generalisation of the A-code to curvilinear line segments at a node. L-codes describe the comparisons of the lengths of the two adjacent line segments with values of “bigger”, “equal”, and “smaller”. The K-code describes the curvature of a curvilinear line segment with values of “convex”, “straight”, and “concave”.

Q-code descriptions of shapes result in sequences of Q-code strings. The general characteristics of Q-codes are:

(i) direction of scanning is counterclockwise;
(ii) encoding can start from any code (normally from a node); and
(iii) components of Q-codes are symbol(s) plus sign value(s).

Table 1 shows how qualitative values are set to shape attributes. The granularity of Q-codes can be changed using a sectioning method, which is a way of segmenting the intervals. Sign values are thus extended, for example, from {+} to {++, +0, +-} as a result.

	A-code / C-code	L-code / K-code
Numeric value range	$0 \leq \theta < 2\pi$	-Ï < l, (k) < Ï
Landmark set	{0, π}	{-Ï, o, +Ï}
Interval set	{[0,0], (0,π), [π,π], (π,0)}	{(-Ï,0), [0,0], (0,+Ï)}
Q-code set	$\{A_{nil}, A_{+}, A_{0}\ A_{-}\}$, $\{C_{nil}, C_{+}, C_{0}\ C_{-}\}$	$\{L_{-}, L_{0}, L_{+}\}$, $\{K_{+}, K_{0}, K_{-}\}$

Table 1. Qualitative value assignments to shape attributes

2.1.3. *Syntax of Q-code encodings and syntactic operators*

In a qualitative representation process, a shape is converted into a sequence of Q-codes resulting in a line of strings called its “primitive code”. Some syntactic regularities can be discovered from the structure of Q-codes. Coding theory has been developed for handling this kind of pattern analysis task (Leeuwenberg and Buffart 1983) with three syntactic operations identified as “iteration”, “symmetry”, and “alternation” (Helm and Leeuwenberg 1986, Martinoli et al 1988) and converts a Q-code to a structured pattern of simpler codes called “end codes”.

Since the major task of the Q-code representation of drawings is to handle shape features, the three types of syntactic regularities of Q-codes become the most generic characteristics of shape description. These syntax can be applied not only to the simple atomic Q-codes but also to bigger chunks of Q-codes with significant design meanings associated with them.

2.2. SYNTACTIC STRUCTURE FOR SHAPE FEATURES

Shape features are recognisable, definable, structural patterns, ie., shape features are named entities with distinctive structural patterns from which the physical characteristics of design objects are understood and explained. These shape features are found in the drawings describing designed objects, but when they are encoded, it is often not clear how to distinguish one from another. It is possible to draw an analogy with the structure of natural language in order to explain how the syntactic structures in Q-codes are related hierarchically to each other.

Table 2 shows levels of shape features described in linguistic terms, referring to different aspects of shapes. A word, as a minimum and discrete unit of information, can contain a basic shape feature. The words are then aggregated to construct more complicated expressions in the form of a phrase. A Q-phrase displays a certain syntactic structure of one or more Q-words by explicitly describing the structure with a set of syntactic operations such as “iteration”, “alternation”, and “symmetry”. These smaller shape features are aggregated to form a complete and closed shape termed a Q-sentence as another level of shape features.

Levels of shape feature	Reference to the shape
Q-code	A simplest symbol which refers to an atomic component of a shape attribute.
Q-word	A sequence of Q-codes which refers to a shape pattern with distinctive design significance – a shape feature.
Q-phrase	A sequence of Q-codes in which one or more Q-words show a distinctive pattern of structural arrangements.
Q-sentence	An aggregation of Q-codes, Q-words, and Q-phrases so that it refers to a closed and complete contour of a shape.
Q-paragraph	A group of Q-sentences where necessary spatial relationships are described with specific connectives.

Table 2. Various levels of shape features with their linguistic analogy

2.3. SHAPE FEATURES FOR DISCOVERING DESIGN SIGNIFICANCES

Recognising patterns that match the description of an object is a method widely used in pattern matching and pattern recognition. The pattern matching algorithm identifies some interesting patterns in the given descriptions of shapes. A primitive description of a shape is nothing but a sequence of symbols which in itself does not reveal any design significances or design meanings. No display of syntactic structure in the primitive encoding of a shape leads to recognition of possible functions those structures might perform. Identification of shape features from the given primitive encodings will eventually fill the gap of correlating structure descriptions with function descriptions. Identification of Q-words and Q-phrases from a given Q-sentence therefore becomes one of the major tasks in the qualitative modeling of shape.

2.3.1. *Methods for syntactic shape feature recognition*

The following steps outline the analysis of the qualitative representation of shapes using syntactic shape feature recognition.

- Given shapes are encoded with a set of Q-codes to form Q-sentences. Both A-codes and L-codes are used at the coarsest level of granularity.

- All the possible Q-words are systematically generated by using words of increasing length and then the codings are searched to determine if the Q-sentence contains the matching Q-word. The number of appearances as well as encodings of the Q-words are counted.
- The matching results are plotted in a graph with the length of the Q-word and the number of appearances as the axes. The significance of the Q-word increases as either the length of the Q-word or the number of appearances increases.
- Significant Q-words are analysed in terms of Q-phrases. Hence the qualitative design characteristics of the shape are analysed in terms of some meaningful design semantics.
- To determine symmetry a Q-phrase is firstly searched by looking for the inverse pattern of the Q-word. Then the reflective symmetry pattern (palindrome pattern) is checked for.
- Finally, the results are interpreted.

2.3.2. Three examples

Figure 1 and Table 3 show three shapes with their Q-code encodings. These three shapes are chosen from a group of church plans (Schnell 1974) which illustrate shape patterns for church spaces such as “altar”, “bench” and “entrance”.

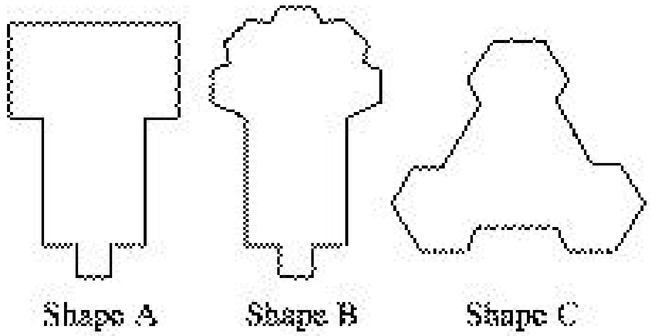


Figure 1. Three shapes chosen for shape feature recognition

Q-code	Shape A	Shape B	Shape C
A-code	$(A_+ A_+ A_+ A_+ A_- A_+ A_- A_+ A_+ A_- A_+ A_-)$	$(A_- A_+ A_+ A_- A_+ A_+ A_- A_+ A_+ A_- A_+ A_+ A_- A_+ A_+ A_- A_+ A_- A_+ A_+ A_- A_+)$	$(A_+ A_+ A_+ A_+ A_- A_- A_+ A_+ A_+ A_+ A_- A_- A_+ A_+ A_+ A_+ A_- A_-)$
L-code	$(L_+ L_- L_+ L_+ L_- L_- L_+ L_- L_0 L_0 L_0 L_0)$	$(L_+ L_- L_0 L_- L_0 L_+ L_- L_0 L_+ L_- L_0 L_+ L_- L_0 L_+ L_0 L_+ L_- L_0 L_0 L_0 L_0)$	$(L_+ L_- L_+ L_0 L_0 L_- L_+ L_- L_+ L_0 L_0 L_- L_+ L_- L_+ L_0 L_0 L_-)$

Table 3. Q-code encodings of the three shapes

2.3.3. Q-word recognition

Possible shape features (Q-words) are searched for from the given shape descriptions using a generate-and-test method. Firstly, all the possible Q-words are generated. At the coarsest level of granularity, A-codes and L-codes are composed of two and/or three basic Q-codes respectively, namely {A_+, A_-} and {L_+, L_0, L_-}. Possible numbers of Q-words for a length *n* are, therefore, 2^n and 3^n for each A-code and L-code case. Secondly, the appearances of each Q-word are checked in terms of "iteration (alternation)" and "symmetry" operations. As for iteration, even overlapping Q-words are counted respectively. For example, when the Q-word "(A_+ A_- A_+)" is searched for, its iterative appearance in the Q-sentence (A_+ A_- A_+ A_- A_+ A_-), it is counted as "3". For symmetry, Q-words (Qw) are counted if it is possible to describe a Q-phrase using symmetric operations as **S**[Qw1 Qw2]. Figure 2 shows the result of Q-word recognition in terms of the iteration (alternation) operation from the given shapes A, B, and C.

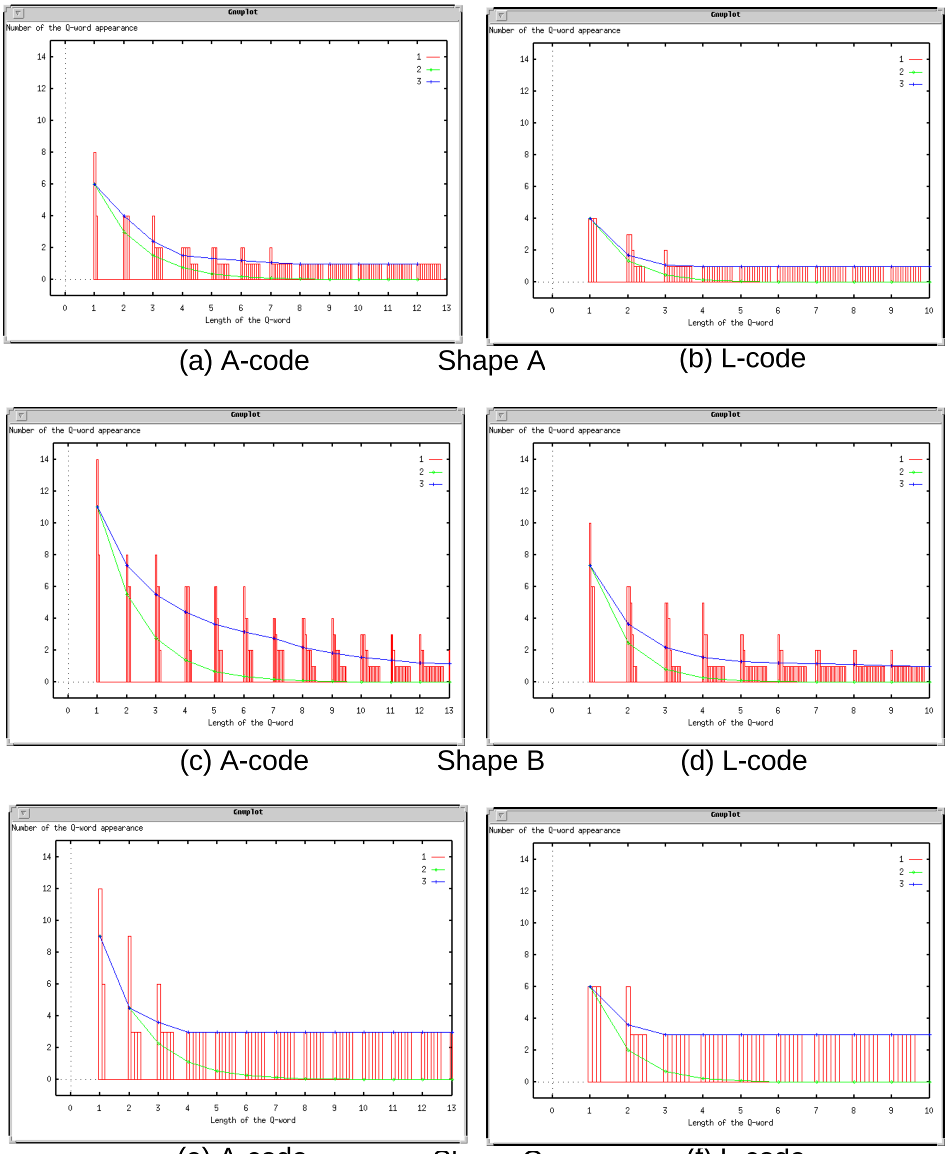
3. Results

The following can be observed from these results.

- When the total length of a Q-sentence is *n*, there are *n* Q-words, ie., therefore, including all the overlapping Q-words, the sum of all the appearances of each Q-word of the same length equals *n*.
- Any Q-word with the number of appearance greater than 1 implies something structurally meaningful. If that Q-word is longer in length than other Q-words with same number of appearances, then it can be interpreted as having more structural significance than the other. Hence the most meaningful Q-word(s), with longer length and larger number of appearances can be interpreted as being related to design concept of that shape.
- As the length increases, the average of Q-word appearance converges to certain values. There are two types of averages considered. One is the average of Q-word appearances among all the possible Q-words. This number eventually converges to 0. The other is the average of Q-word appearances among the identified Q-words. This, in most cases, converges to 1 which means that all the different Q-words are recognised. When the second average converges to an integer number *i* greater than 1, it is interpreted as that the shape has (syntactic) rotational symmetry of "$2\pi/i$"

Among the Q-words identified from the shapes A, B, and C by the iteration operation those Q-words with the largest number of appearances and with the longest lengths are chosen to be examined in Table 4. Q-words of length 1 are excluded from the table because of their lack of information as a "word".

Table 4 displays some findings from the shape-feature matching results. The "wedge shape" (A_+ A_- A_+) seems to be a dominant shape feature in the description of shapes A and B, while a multiple interpretation is possible for the longer Q-words in shape B either as a sequence of "wedges" or a sequence of "protrusions" (A_- A_+ A_+ A_-). A type of "activity pocket" (A_- n*(A_+) A_-) proves to be a dominant shape feature which iterates



(a) A-code Shape A (b) L-code

(c) A-code Shape B (d) L-code

(e) A-code Shape C (f) L-code

Figure 2. Identified shape features from the three shapes in Figure 1, derived by counting the occurrence of Q-words in the Q-code representations

many times to form a 2π/3 rotational symmetry. In the L-code descriptions, some repetitious Q-words are found in shapes B and C such as ($L_- L_0 L_+$) and ($L_+ L_0 L_0 L_-$) whereby these patterns of length change characterise those shapes.

Shape	Appear. & Length	Q-word (A-code) up to length 12	Appear. & Length	Q-word (L-code) up to length 9
A	4 & 3	$(A_+ A_- A_+)$	3 & 2	$(L_0 L_0)$
	2 & 7	$(A_+ A_+ A_- A_+ A_- A_+ A_+)$	2 & 3	$(L_0 L_0 L_0)$
B	8 & 3	$(A_+ A_- A_+)$	6 & 2	$(L_0 L_+)$, $(L_- L_0)$
	3 & 12	$(A_+ A_- A_+ A_+ A_- A_+ A_+ A_- A_+ A_+ A_- A_+)$	2 & 9	$(L_- L_0 L_+ L_- L_0 L_+ L_- L_0 L_+)$
C	9 & 2	$(A_+ A_+)$	6 & 2	$(L_- L_+)$
	3 & 12	$(A_- A_+ A_+ A_+ A_+ A_- A_- A_+ A_+ A_+ A_+ A_-)$	3 & 9	$(L_+ L_0 L_0 L_- L_+ L_- L_+ L_0 L_0)$

Table 4. Significant Q-words identified from the shapes A, B, and C in Figure 1

Another interesting aspect of shape feature matching is the variation in the numbers of significant Q-words, ie, those Q-words that appear more than once. There are two patterns of either “increase-decrease” or “increase-steady”. Shape features $\{(A_+ A_- A_+)\}$, $\{(A_+ A_+ A_- A_+ A_+ A_- A_+), (A_+ A_- A_+ A_+ A_- A_+ A_+), (A_- A_+ A_+ A_- A_+ A_+ A_-)\}$, $\{(A_+ A_+ A_+ A_+), (A_+ A_+ A_+ A_-), (A_+ A_+ A_- A_-), (A_+ A_- A_- A_+), (A_- A_+ A_+ A_+), (A_- A_- A_+ A_+)\}$ are found at word lengths 3, 4, and 7 for shapes A, B, and C respectively. The dominant shape features seem to emerge around these points such as $(A_+ A_- A_+)$ for shape A, $(A_- A_+ A_+ A_-)$ for shape B, and $(A_- A_+ A_+ A_+ A_+ A_-)$ for shape C.

Discussion

Qualitative modeling of shape distinguishes itself from quantitative modeling in a number of significant ways. It describes with classes of shapes as opposed to quantitative modeling which describes individual shapes. This distinction is significant because qualitative modeling does not require the specificity of values which are only available later in the design process. The utility of qualitative modeling is partly founded on this distinction. The effects of the availability of qualitative modeling of the kind introduced in this paper can be grouped into the following categories:

(i) tools to support conceptual designing;
(ii) reasoning about shape; and
(iii) relating shape to space.

It now becomes possible to construct computational tools to support conceptual designing since there is no requirement that drawings be precise as is the case with most other tools. The designer does not need to take numerical decisions until later and can concentrate on shape as a class descriptor rather than shape specified through geometry.

Since shape features are now modelable it becomes possible to reason about shapes through their features unrelated to their specific geometries. This has the potential to open up new areas of computational support for designers..

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