COMPUTATIONAL METHODS FOR SHAPE MANIPULATION IN GENERATION
A LITERATURE REVIEW

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ABSTRACT

In this paper we will present a state of the art of the descriptive and generative models for shape. We will present several different approaches for the manipulation of shape in computational systems: numerical models, graph models, descriptive models. This investigation will lead to a discussion regarding the use of these models for supporting the generation of shapes in the early phases of the design process.

Keywords: *design, shape description, shape generation*

1. INTRODUCTION AND FOCUS OF RESEARCH

There is a quite common list of tools that can be used for computer-aided design in the late phases of the design process. These tools support the detailed design phase, where designers develop a product architecture, and specify shapes corresponding to the product physical features. It is quite less common to find tools for supporting the early phases of the design process, where designers imagine and provide shapes, concepts and ideas for innovative products. These tools have been investigated in the context of the GENIUS project†. This project consists in the elaboration of a categorization and generation system for designers. Considering the design process [1,2], this system intends to support the generation phase (generation of solutions, sketches, identification of a "good shape"). In order to do so, several issues have to be adressed : the modelisation of the designers cognitive process, the

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elaboration of an artificial intelligence system that incorporated designers' knowledge, and the designing of an interface for letting the designers manipulate the system's data and results. In this context, we have particularly focused on a state of the art of the technologies that would let a computational system manipulate and compute shapes.

This paper will present the result of this investigation as a state of the art that will cover different technologies, starting with those to support information retrieval. We investigate 2D and 3D techniques that provide descriptors for shape analysis and retrieval ; for that we will provide a broad definition of shape analysis and a caracterization of the techniques related to this issue. In a second part, we will detail technologies that are related to the numerical description of shapes. In a third part, we will discuss the capacity of these technologies to fit with the designers' cognitive processes. More particularly, we discuss the fact that a composition of several models, and means of cooperation between these models, has to be achieved in order to cover the shape generation process [2] from the very beginning (generation of random shapes) to the end (detailed sketching).

In relation with our objectives – the elaboration of a creative shape generation system – we will propose perspectives of development for a combined model of shape taking into account several descriptors in order to support the shape generation phase in design.

2. SHAPE MANIPULATION EXPLAINED

In order to define and propose shape manipulation techniques adapted to the needs of the designers in the early phases of shape synthesis, we have investigated several approaches in the literature. These approaches are presented here corresponding to a classification into several categories corresponding to their basic features and functions. We will first present a broad overview of the applications of shape analysis in computer systems. We will then present a caracterization of shape description by the fundamental concepts of this issue. Then we will present the categories of our survey and the corresponding techniques. Finally, a synthesis will provide an overall view of the topic.

2.1. Applicative caracterization of shape analysis

According to [3], shape analysis is important to many modern applications of computing systems, in several fields such as biology, computer-aided design, the military domain, computer vision, entertainment, etc. These applications can be characterized by the following basic problem types [3] :

- matching : to be able to compute the similarity between two shape models and characterize their differences,
- registration : stronger than matching, this means to be able to align two models optimally and visualize their similarities and differences,
- retrieval : in a database of shapes, to be able to find the models that best match a given shape query
- recognition : stronger than retrieval, this means to be able to find shapes that match a shape query, and also to be able to determine if these shapes don't match the query (for instance for hand print recognition in a database of suspects),

- verification : to be able to determine if two shapes match within a given tolerance (for defect detection, or CAD part verification),
- clustering : given a database of 3D models, to be able to provide a partition of this database considering the similarities and dissimilarities between the models,
- classification : given a set of shape class specification and a given shape, to be able to know to which class this shape belong,
- feature detection : to be able to detect geometric features of interest on a shape,
- segmentation : to be able to split a shape into several salient parts,
- synthesis : to be able to automatically synthetize new examples of a given class of shapes,
- semantic labelling : to be able to infer semantic meaning regarding a given shape model (either for finding its purpose, function, or its semantic or emotional description).

This categorization [3] provides a clear overview of the mecanisms that are required in order to manipulate shapes within computational systems. In each of these applications, one will have to determine how shape will be described, what can of features are required in order to achieve the task. For instance, the descriptions used to retrieve shapes within a database will tend to be light, in order to reduce the computation time of the request; they will also provide a broad definition of the shapes, tending to let some tolerance in the definition of the similarity between the shapes. On the other side, description techniques used to recognize shapes within a database, or to match two shapes, will tend to provide a more detailed description of the shape; this is linked to the level of precision and accuracy that the system will have to provide to the user. This will lead to a competition between description techniques based on their technical performance, such as its efficiency (is it fast or slow) and its discriminative power (is it high or low). Other features of descriptors such as their inner fundamental definition will be an element of comparison for determining which one corresponds to which function.

2.2. Fundamental caracterization of shape description techniques

Shape matching, retrieval, clustering, etc. cover different aspects of a same problem: how numerical systems can be able to manipulate and use shape within specific computations. This problem, addressed since the early stages of computing, first through the problem of shape digitization, has diverged into several sub-problems such as drawing, image segmentation, shape recognition, etc. Through all these questions, common features have been investigated, that can be considered as the fundamental aspects of shape, or conceptual features of shape descriptors. Whether we consider different aspects of the definition of an object and its shape, we will turn to different description techniques.

2D / 3D - the notion of object shape is intrically linked to the appearance of this object in a visual context. We are used to manipulate object within a three dimensional space, and consider its shape through its volume, mass, colors, etc. In computer systems, we observe two different domains that are quite distinct in the literature: the three dimensional domain where we find 3D models of objects and the two dimensional domain that is related to images or videos of objects. These two domains are connected, and because the techniques sometimes can be transposed from the 2D domain to the 3D, the surveys regarding 2D [4] or 3D shape analysis [5,6,7,8,9] are usually refering to works falling in both. Though, it is not possible to make a perfect match between the techniques related to 2D and 3D.

Region versus contour - considering an object, and its appearance on an image or a video, we can take two different approaches to caracterize its shape. First, we can consider its area, which is represented by some extension of the numerical space, that is for instance a set of pixels that covers some part of an image. Considering this, specific descriptors can be used to extract features from this set of pixels. The second approach is to consider the contour of this object. This contour is given by the points on the boundaries of the object. Since the beginning of visual signal processing, specific algorithms have been designed in order to extract these boundaries from numerical images (for instance by filters extracting points that are located on a significative change in the visual signal, hence representing a point between two visual areas).

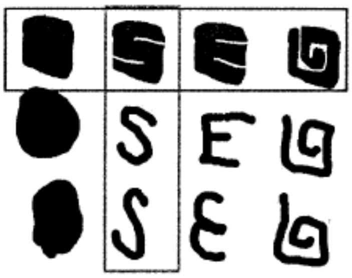

Figure 1: Shape as a region versus shape as a contour (from [10])

Considering the shape of objects as regions or contours, does not cover the same notions. In, [10] the authors provide a clear visual example of the distinction. On figure 1, the different shapes can be considered either as regions or contours. But when considering these objects as regions, objects in the first row have common spatial distributions of pixels. They will be considered as similar using region-based descriptions, even if they don't have the same contours. On the other side, objects in the second column have similar contours, but don't have the same region-based description. Using contour-based descriptors, these S-shaped objects will be considered as similar [10].

Invariance - this is a common question in the descriptors used for shape : should the description be invariant relatively to some shape transformations? Most commonly, this question relates to the fact that similar shapes can be found in different configurations. In some contexts (such as object recognition within images), integrating an invariance on rotation will be capital in order to detect shapes that may suffer various rotations due to their context (places on a map that may not be oriented, objects in a scene, etc). In other contexts, this rotation will be meaningful, as for instance in design an angle can denote an orientation, a dissimetry or an overall "speed" given to a shape. In different applications, other kind of invariances can be investigated : invariance to scaling, to an affine transformation (see figure 2), etc [11,12].

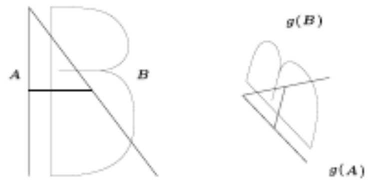

Figure 2: The shape on the left is an affine transformation of the shape on the right (from [11])

Robustness - this other question relates to the property of a descriptor to be robust in relation to shape modification. This is different from invariance, since here the robustness quantifies the capacity of the descriptor to be stable under variable conditions: introduction of noise, of variability in a contour, introduction of some protusions, etc. This issue is particularly important in the part of shape analysis that relates to the description of shapes extracted from 2D images. Considering the issue of segmenting an image into objects [13, 14], for instance, on figure 3 you can observe examples of shapes extracted by image segmentation. These shapes can present several imperfections related to the quality of the visual signal (variations in pixels), and to the quality of the segmentation algorithm.

Figure 3: Examples of shapes obtained by segmentation of images, presenting problems contour variability [15]

Other factors can be crucial to the interpretation of shapes. For instance, the question of the **structure** of the shape requires being able to store the configuration of the sub-elements composing a shape [16]. Rather than considering the shape on a global view, this leads to a configurational view of the shape (either with graphs or trees) capturing its inner structure and describing its structuring elements with specific descriptors. Also, the issue of managing **occlusions** of the shapes can be important in shape retrieval or shape matching contexts. In real context, shapes can be occluded by other shapes (for instance one object passing in front of another in a video), or parts can be missing in a shape (because it hasn't been extracted properly). In this case, techniques can be used to operate a partial matching of two shapes in order to find correspondances between segments [17].

All these fundamental aspects relate not only to shape description but also how shape will be understood and manipulated by the system. Weither these aspects should be investigated or not, and which answers can be given to these issues related to the need of the user (or the system) in supporting the shape analysis functionalities.

3. SHAPE DESCRIPTION TECHNIQUES

In this section, we present a broad overview of the description techniques used in shape analysis and manipulation. This overview presents a selection of works (10 among 60, because of the paper format) that are representative of what can be found in the literature that capture different aspects of shape. Most of these descriptors come from the image retrieval field [14,18], where the focus on shape has led to the production of systems able to retrieve images using shapes extracted from the visual signal. Also, the developping field of 3D shape retrieval [4,7,8] has led to the production of more complex descriptors linked to the description of 3D models.

The first family of descriptors is the simplest one. It consists in the extraction of **broad features** from a given region or contour. These very global indicators are used to describe the most evident features of shapes such as its volume, area, compactness or symmetry. Simple measures have been developped and used in the field to quantity these features [19,20]. Also, generic statistical moments have been applied [19,20] that capture the basic elongation, symmetry, configuration of the shape. For instance, it is possible to establish the global balance of a region using statistical moments.

The second family of descriptors is more detailed and provides a global **decomposition** of the shape along different dimensions. For instance, shape histograms [21] can be computed, that capture an overall distribution of orientations along a contour, or within a given area. Local descriptors (angles, curvatures) are then agregated along an histogram. Just as color histograms capture a distribution of colors that operates a global fusion of every local property of the image, shape histogram are a rather classical way to match shapes with a request in a retrieval application, but they lack the detailed description of local features that would let a system operate a discriminative matching between two shapes.

Another example of a decomposition of shape lies within the different tools used to extract harmonics, or to decompose the signal of shape along a signal base. In this category falls descriptors linked to spherical harmonics [22], that consists in the projection of the object along a unit sphere, and applying a fourier decomposition on the distance vectors obtained by relating the shape to the sphere. The result obtained (see figure 5) let the descriptor be adaptable to a level of detail needed to describe the shape. This is also the case in wavelet decomposition [23] that can be used to extract spatial frequencies along a contour, or on the surface of a region.

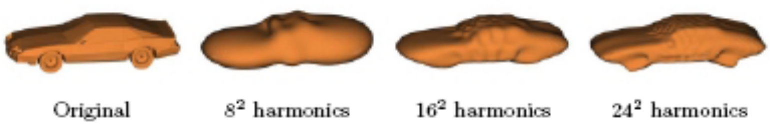

Figure 4: Spherical harmonics, from [23]

Finally, the curvature scale space [24], used in the MPEG-7 descriptor standard, consists in applying smoothing operations to a curve and observing the point at which salient curvatures disappear along this process. This leads to an identification of caracteristic points that describe the major curvature change within the shape (see figure 6).

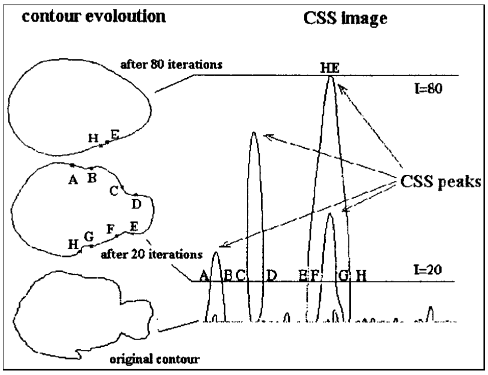

Figure 5: Curvature scale space, from [24]

The third family of descriptors regards the decomposition of shapes (more particularly 3D shapes) as **graphs**. The first orientation in this field is to exploit the data available in the CAD tools. This is basically what [25,26] do : by using the design graph and its logical and semantic description, the system can propose matching capabilities that rely on the structure of the object designed, and also reflecting a similarity between every component of this object. For instance, it becomes possible to query a database of CAD parts using a design model, to look for equivalent or similar configurations of objects, and obtain other design models letting the designer build upon them. This is particularly applicable when this information relative to CAD is available. In other contexts, it is still possible to extract a significative structure from the mesh models. For instance, [26] has proposed a skeleton model, derived from the shape volume by finding points that match some specific criteria computed on a sphere included within the shape and centered on the point. This way, the authors obtain a graph decomposition of the shape, with nodes capturing points of the structure, and edges their spatial relations (see figure 7).

Finally, some other shape descriptors rely on views. This is related to the fact that a shape can be seen along multiple views, and that matching two shapes correspond to a matching between every possible view of these two shapes. Corresponding to this idea, [27] propose a decomposition of a 3D shape along several views, each of these views providing a 2D description of the shape. These descriptions can also be used as a base to extract 2D descriptors from each of the views, then creating a multiple-view description.

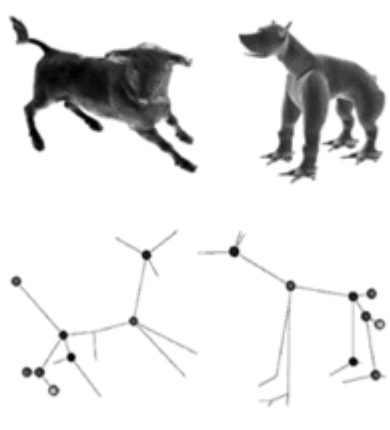

Figure 6: Skeletons of 3D shapes, taken from [26]

4. DISCUSSION

As we have explained in our introduction, our goal is to prepare the elaboration of a system supporting the early phases of the design process, and particularly the tasks related to information categorization and shape generation. More specifically, we intend to design a system that will assist the designer in the production of shape concepts and early sketches, by providing him with shapes, descriptions, and letting him diverge and converge to obtain "good" shapes. In this perspective, the investigation of artificial intelligence techniques to capture shapes and compare them was a prime objective. As we have seen previously, the manipulation and description of shape in computational systems has been explored in different ways for different purposes. Our point here is to discuss the applicability of these techniques for a system capable of understanding and manipulating shape like designers do in the early phases of the design process. Considering our previous studies of this design process [2], we focused on the very early phases, where designers produce sketches that can vary from a very first random shape ("splash") to a very complex sketching incorporating semantic and formal attributes. Along this process the designers will develop ideas, concepts and produce more details as long as they do. In the context of this design process, it is capital to be able to determine what kind of shape description and manipulation techniques can be used to capture the nature of the shape manipulated by the designers.

In the state of the art presented, we have seen that there is a different level of precison exists among shape descriptors. Considering the evolutive nature of the shapes in the design process, it is likely that not only one but different descriptors will be required, corresponding to the evolution of the ideas of the designers. Broad descriptors can help us quantify and describe shapes in the very beginning, hence capturing broad parameters of the early divergent shapes produced. Once the first steps passed, more precise techniques could be used to capture details regarding the global shape that is being designed. As far as the process goes, incorporating more details and structure, a structural descriptor (such as a skeleton or a model graph) can be used to match different solutions and compare their respective features, helping the designers to sort out many possible solutions and qualify their advantages. On the other hand, the level of precison required is not the only factor of choice among descriptors. At some point in the production of sketches, it will become important to incorporate relations between shapes that let the designer merge and split different parts of the shapes. The same way we have pointed out mecanismes that let the system operate partial matchings, we will need to be able to relate sub-parts of the curves and objects one to the other. What could be unnecessary considering the very first random or simple sketches, will become important as long as the designer provide a precise intention in its shapes. If this is for the moment an unresolved issue, it is likely that many of the descriptors presented will be required in order to support the different stages of sketch production in early design. Integrating different levels of precision (broad or coarse), and different levels of description (object, sub-parts) will let the system cope with different levels of understanding of shapes that are all entailed in the early design process.

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