A Computer Aided Model for Copy-and-Paste Editing in the Industrial Design Cycle

by

Charles Dumont

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

This thesis represents work was really to do computer aided design by thinking about shapes and forms. More specifically, the goal of this work is to provide industrial designers with an intuitive mechanism for transferring brand-identity elements from one object to another, and to allow manual modifications of physical prototype details to be scanned and reincorporated back into original digital models.

An algorithm to copy-and-paste freeform details from one freeform surface to another using displacement field and planar parameterization operators is presented. A tool based on the algorithm is developed such that, from the designer's viewpoint, details from one surface can be mapped to another in two steps: the selection of the detail to transfer (copy); and the choice of the surface onto which the detail is to be mapped (paste). A proof of concept has been implemented and is used to demonstrate the capabilities of the framework.

In conjunction with this surface Copy-and-Paste the concept of example based modeling is introduced as a more intuitive approach to form design. This new concept places the Copy-and-Paste application in a more natural framework. An application for 2D and 3D sketching text for the Copy-and-Paste tool.

Thesis Supervisor: David R Wallace
Title: Associate Professor

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Chapter 1

Introduction

1.1 Motivation

Industrial design is an important aspect of product design because it addresses the form of products from the user's viewpoint. It is understood that consumers often buy products not only because they are affordable or simply functional, but because they suggest an irresistible experience [6, 19].

From a product development firm's viewpoint, industrial design, or product form, plays an important role in both differentiating product offerings from competitors and in implicitly conveying the personality of the company to the consumer. The term branding –putting the company's signature on the product– is often used to capture these concepts.

Branding is a very important tool to control the consumer's perception of a product. It basically allows the manufactures to identify a product not only by its intrinsic qualities but to values and feelings shared by the targeted market. For example, it explains why, in many product advertisements, no mention of the performance and price are made. The product is instead presented in a way that conveys the values associated with the potential consumers. For example, most people will instantly recognize, independently of the vehicle's specific model, a Volvo vehicle as a Volvo and

associate it with safety –which may be something important for a family. Similarly, most Mercedes vehicles are easily recognizable as such and are associated with luxury –an aspect potentially important to rich people.

While it is accepted that form elements and details are important factors in creating a brand identity, it is difficult to algorithmically codify these brand defining elements. However, skilled industrial designers seem to be able to establish coherent form themes across products and thereby establish consistent user expectations and brand identity.

In order to assist designers in the form definition and branding process, a computational tool has been developed that helps designers transfer form elements from the context of one product to another. Such form elements may be either scanned surfaces or digital surface models. Key challenges are that form elements are neither easily parameterized nor decoupled from the basic shape of the product. Therefore, the brand form elements are difficult to extract explicitly and integrate with another design.

This thesis presents a framework to extract and transfer brand identity elements from one surface to an other. The work is divided into two principal sections: the first defines the Copy-and-Paste operator and describes the underlying principles. The second part discuses a modeling interface for 2D and 3D sketching and introduces the concept of example based modeling, a high level concept that allows the user to use the 3D Copy-and-Paste tool in an interactive fashion.

More specifically, the first part of this thesis focuses on an application of Computer in the domain of industrial design. The proposed tool is a transposition of the Copy-and-Paste metaphor into the 3D shapes domain. The global aim of the work is to allow designers to select features they like on existing products and to integrate this feature into a new design. Two main applications for this tool are shape reuse

and product branding.

The second part of this thesis presents a concept to speed up the work of industrial designers and stylists in the early stage of the design process. It illustrates how the Copy-and-Paste tool could be used in an interactive and novel way by taking advantage of the contextual information available in the first steps of the design. The 2D and 3D sketching interface is first presented, then the concept of example based modeling is explained using an illustration inspired by car styling.

Chapter 2

Background

2.1 Design and Computers

For the past decade Computer Aided Design (CAD) software has been used extensively in engineering design. For example, in the automotive industry CAD software are well established at most steps of the design process such as manufacturing and finite elements analysis. Due to the type of problems tackled by engineers (dimensional and process defined), it has been relatively straightforward for software developers to create CAD packages that serve their purposes well.

This work targets the stylists and industrial designers who works at the earliest stages of the design process, namely on forms and shapes. Designers exclusive non-verbal language and techniques has made difficult to produce a complete and integrated Computer Aided Industrial Design (CAID) system. But, motivations for CAID system are numerous: they include improved speed, effectiveness and quality of both design and decision. CAID potentially provides a greater freedom for designers to explore a wider range of alternatives fluidly and quickly. It also includes potential for collaborative engineering processes with the creation of common databases and a more integrated overall approach [27]. There is an important link from styling to engineering that can be done using computer systems.

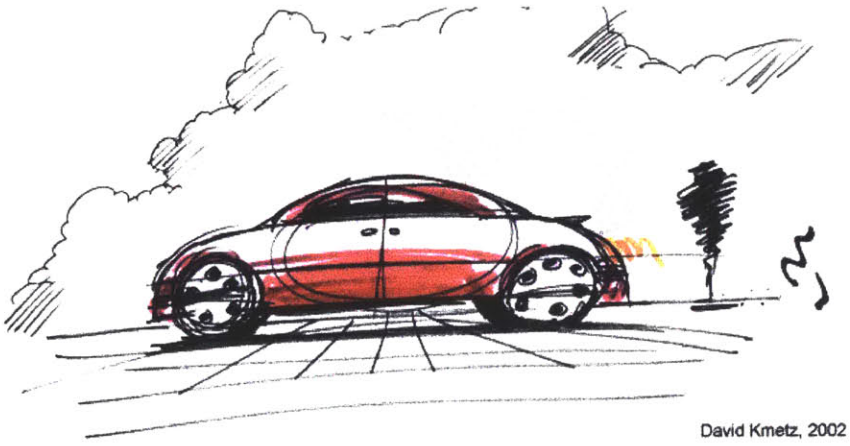


Figure 2-1: An example of a hand-sketched concept car.

At the beginning of the design process, the emphasis is on concept sketches. Today, in most car companies, much of the overall vehicle concept is digital 2D. Designers sketch on top of skeletal layouts of the overall vehicle hard points (wheel-base, seats etc.) with systems which are highly tailored for the car application. Conversely, the people that design things like radios and dashboards typically do sketches on paper and then move to CAD to refine details. Also, product design firms do many different products and insist on a lot of hand sketching. Initially, the attempt is to create a proposal as a whole, keeping the work on details for a later process. The responsibility for the conceptual design stays in the hand of the stylist until a high level of detail is reached. After the concepts are narrowed down, the industrial design person works with surface modelers to create 3D surfaces for the concept. The digital models are then used in computer numerically controlled machines to rough-out clay or foam models. Then additional detailing and refinement is done by hand and through digitalization. When the design is handed over to the engineers, it often goes through a redesign and optimization process in order to get an engineering friendly design.

The automotive industry is so economically important that it can develop it own specialized styling software. This means that the software is developed in a way that takes advantages of the typical requirements and physical composition of the product.

Besides, in the automotive industry the configuration, package and engineering details stay pretty much the same from one model to the other [27]. But, although the packaging (ergonomic, operational and mechanical) is crucial to the entire process, it has no utility for the form creation, instead it is seen as constraints.

The remaining part of this section is dedicated to the definition of the needs to improved Computer Aided Industrial Design applications. These needs represent the factors that drive the design of the applications presented in this thesis. They are divided in three categories: stimulating environment, intuitive interface and integrated system.

- *A stimulating environment*

The CAID packages should offer a fun and stimulating environment for design. The environment should not limit the action of the designer, instead it should allow an easy and rapid evaluation of concept designs. The tool should also include the possibility to include external constraints into the design, such as packaging. The system should also be able to orient the designer towards solutions for branding. The designer should have the possibility to integrate artifacts into his design through reverse-engineering.

Recent CAID environments strive to stimulate creativity by providing a wide variety of design options (not by suggesting any design options). These tools are used to create and alter shapes, form and surface qualities of 3D models. They excel at presenting concepts with photo-realistic rendering and lighting effects.

- *An intuitive interface*

A CAID tool should allow designers to easily modify their designs. The operations must be as simple (in this context, simple means natural and not trivial) as possible and their number must also be limited. The system must easily deal with mathematical constraints (eg. tangency, continuity, boundary conditions) and should hide

most of those low level constraints to the normal user, without limiting user actions. The Teddy system [10] is a good example of a system with an appropriate level of operators. It makes a big difference in the measure of the intuitiveness of the interface.

- *An integrated system*

Industrial designers want their design to be kept as intact as possible throughout the production process. As discussed in the previous sections, engineers often have to change the original propositions because they do not fit into mechanical or production constraints. To avoid these problems, good communication is needed between departments: industrial designers must understand and integrate engineering constraints into their design engineers must understand the aesthetic design intents. The CAID systems should produce design usable without changes by the downstream process.

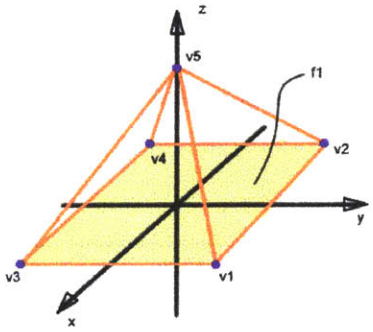
The key to a good design interface is allowing geometric manipulation to match the way designers think about forms. This way, intuitiveness and stimulation come for free while the integration can be taken care of at another level. We claim that the 3D Copy-and-Paste tool presented in the next chapter is a good example of such a tool because it offers a mapping between ideas such as "I want an feature like this one" on the designer side to a concrete operation on the software side.

2.2 Computational Geometric Representation

2.2.1 Polygonal Meshes

Polygonal meshes are very commonly used in computer graphics applications. Their main advantages are their simplicity, robustness and computational efficiency. Meshes can be though of as a piecewise representation of a higher level graphical object. A mesh is always a numerical approximation of the real objects and is typically used

only for the purpose of visualization or analysis. As a mesh becomes finer the approximation of the object improve, but to serve our purposes in computer graphics it is only necessary to define a mesh that is finer than the resolution of the hardware or user perception. The three fundamental features of a typical mesh are the vertex, edge and face (facet). The most fundamental purpose of the mesh is to encode these elements and the relations between them, which is refer to as connectivity (Figure 2-2). This section describe the data structure which is used in the 3D Copy-and-Paste application.



# pyramid.obj		*header*
5 5		*The object has 5 vertices and 5 faces -*
v 1 1 0	v_1	*The vertex* v_1 *is located at* $x = 1, y = 1, z = 0$
v 1 -1 0	v_2	
v -1 1 0	v_3	
v -1 -1 0	v_4	
v 0 0 2	v_5	
f 1 3 4 2	f_1	*The face* f_1 *connects in order*
f 1 2 5	f_2	*vertices* v_1, v_3, v_4 *and* v_2
f 5 3 1	f_3	
f 4 3 5	f_4	
f 2 4 5	f_5	

Figure 2-2: The wire-frame representation of a square base pyramid with the corresponding mesh expressed in *.obj* format (AliasWavefront). The first character of each line define the feature described on that line. The vertices are numbered in order of appearance in the list. Faces are defined using the vertex numbering.

2.2.2 The Doubly Connected Edge List

The Doubly Connected Edge List (DCEL) is a mesh data structure made of three lists: vertices, edges and faces. Its name comes from the fact that the mesh connectivity is encoded at the edge level. As it will be shown, the DCEL data structure can encode meshes of arbitrary topology and meshes with holes, it is a very powerful geometric data structure that can simplify complicated algorithms when use cleverly.

In our implementation of the DCEL, an edge is represented by two half-edges (Figure 2-3). Because half-edges are related to only one face at a time that, they are preferred to the conventional edges. While an edge is an non-directional geometric construct, the half-edge is a directional geometric construct. Figure 2-3 illustrates the difference, the edge $e1$ spans the gap between $v1$ and $v2$ while the half-edge $he12$ goes from $v1$ to $v2$ and inversely, $he21$ from $v2$ to $v1$.

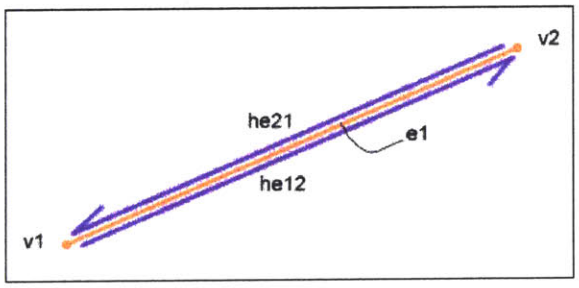


Figure 2-3: The difference between edge (in orange) and half-edge (in blue): an edge is non-directional while a half-edge is directional.

Using the DCEL, the programmer must make a trade-off between memory and speed. Usually, the more data that is stored –increasing preprocessing time and memory usage– the faster is the execution at running time. The structure of the DCEL used in this work has few redundancies which allows for faster computation and simpler code. The respective structures of the basic elements of the DCEL are given in C-style pseudo-code in Figure 2-4.

```
Struct Vertex {
    Double[3]   position;     Cartesian position of the vertex
    Halfedge    halfedge;     A half edge which has the vertex as a starting point
    Double[3]   normal;       The vertex normal vector
    Double      curvature;    The vertex gaussian curvature
}

Struct Halfedge {
    Vertex      start;        The vertex from which the half edge starts
    Halfedge    next;         The next half edge on the loop contouring the face
    Halfedge    previous;     The previous half edge on the loop contouring the face
    Halfedge    twin;         The half edge on the opposite side of the edge
    Face        face;         The face to which the half edge refer to
}

Struct Face {
    Halfedge    halfedge;     A half edge which is part of the loop defining the face
    Double[3]   normal;       The normal vector of the face
}
```

Figure 2-4: The *Vertex*, *Halfedge* and *Face* structures.

Figure 2-5 illustrates a mesh formed by three faces and the information stored for each basic construct of the DCEL. Notice that the half edge list is the longest, which is true for any geometric model. Also, it is important to notice that the information stored in the half edge list allows the programmer to iterate throughout the faces and vertices. These concepts are illustrated in the next section.

2.2.3 Operators

The DCEL data structure has the clear advantage of offering a structured and well suited way of dynamically storing geometric information about a mesh. Once the information is stored in a DCEL it becomes relatively straightforward to calculate geometric information about the mesh.

Face normal. One of the most basic property of a surface is its normal. Using the cross product, it is easy to calculate the normal to a triangular face (Figure 2-6). To make sure that the normal points in the right direction, the appropriate order of the product has to be chosen. The face normals are used for surface sculpting, visualization purposes and to compute the vertex normals.

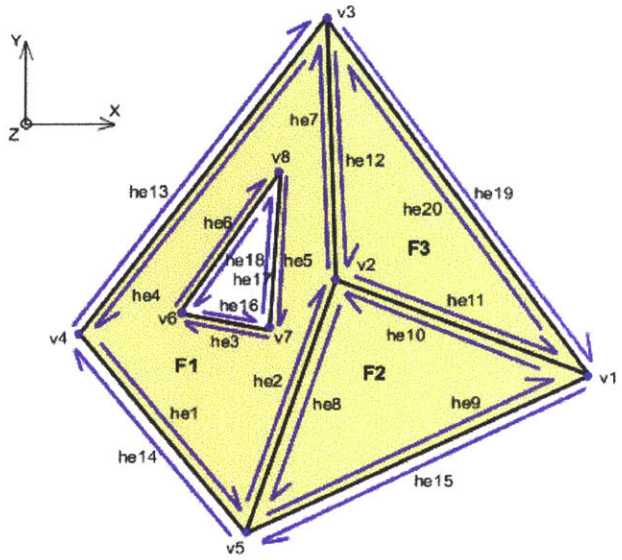
Vertex normal. The vertex normals are critical to calculate the radiance of the model under given illumination conditions. They represents the discrete equivalent (at the vertex location) of the differential case on continuous surfaces. The simplest version of the calculation is presented in Figure 2-7; the vertex normal is given by the average of the face normals surrounding the vertex. A slightly more complex definition weights the face normal by the area of the corresponding surface.

Surface curvature. The previous example illustrates how the DCEL data structure facilitates the calculation of simple geometric elements by allowing easy access to the information related to the vertices, edges and faces. The next example shows how to calculate the Gaussian curvature at a given vertex. Mathematically, a discrete approximation to the surface Gaussian curvature is defines at a vertex as: 2π minus the sum of the angles adjacent to the vertex (Eq. 2.1). The Gaussian curvature is 0 for a flat surface and 2π for a infinitely sharp corner.

$$GC_v = 2\pi - \sum \theta_i, \ \forall \angle \ i \ adjacent \ to \ v. \tag{2.1}$$

The DCEL data structure also offers the advantage of more advanced mesh manipula-

tions; operations such as *edge collapse*, *delete vertex* and *split face*. These operations are of great importance for operations such as mesh optimization and decimation, surface modeling and remeshing.



Halfedge list

Vertex	start	next	previous	twin	face
he_1	v_4	he_2	he_4	he_{14}	f_1
he_2	v_5	he_7	he_1	he_8	f_1
he_3	v_7	he_6	he_5	he_{16}	f_1
he_4	v_3	he_1	he_7	he_{13}	f_1
he_5	v_8	he_3	he_6	he_{17}	f_1
he_6	v_6	he_5	he_3	he_{18}	f_1
he_7	v_2	he_4	he_2	he_{12}	f_1
he_8	v_2	he_9	he_{10}	he_2	f_2
he_9	v_5	he_{10}	he_8	he_{15}	f_2
he_{10}	v_1	he_8	he_9	he_{11}	f_2
he_{11}	v_2	he_{20}	he_{12}	he_{10}	f_3
he_{12}	v_3	he_{11}	he_{20}	he_7	f_3
he_{13}	v_4	he_{19}	he_{14}	he_4	*null*
he_{14}	v_5	he_{13}	he_{15}	he_1	*null*
he_{15}	v_1	he_{14}	he_{19}	he_9	*null*
he_{16}	v_6	he_{17}	he_{18}	he_3	*null*
he_{17}	v_7	he_{17}	he_{18}	he_5	*null*
he_{18}	v_8	he_{16}	he_{17}	he_6	*null*
he_{19}	v_3	he_{15}	he_{13}	he_{20}	*null*
he_{20}	v_1	he_{12}	he_{11}	he_{19}	f_3

Vertex List

Vertex	position	halfedge
v_1	$[x_1, y_1, z_1]$	he_{10}
v_2	$[x_2, y_2, z_2]$	he_8
v_3	$[x_3, y_3, z_3]$	he_{19}
v_4	$[x_4, y_4, z_4]$	he_1
v_5	$[x_5, y_5, z_5]$	he_2
v_6	$[x_6, y_6, z_6]$	he_{18}
v_7	$[x_7, y_7, z_7]$	he_3
v_8	$[x_8, y_8, z_8]$	he_5

Face list

Face	halfedge	normal
f_1	he_2	$[x_1, y_1, z_1]$
f_2	he_9	$[x_2, y_2, z_2]$
f_3	he_{20}	$[x_3, y_3, z_3]$

Figure 2-5: A mesh and the corresponding Doubly Connected Edge List.

```
he = face.halfedge;
v1 = he.twin.start − he.start;
v2 = he.next.twin.start − he.next.start;
face.normal = (v2×v1)/|v2×v1|;
```

Figure 2-6: Code to compute the normal to a triangular face.

Vertex Normal

```
he = vertex.halfedge;
n = 0;
sum = [0, 0, 0];
do{
   sum = sum + he.face.normal;
   n = n + 1;
   he = he.twin.next;
}while(he ≠ vertex.halfedge);

vertex.normal = sum/n;
```

Vertex Curvature

```
he = vertex.halfedge;
angle = 0;
do{
   v1 = he.next.start − he.start;
   v2 = he.previous.start − he.start;
   dp = (v1)/|v1| · (v2)/|v2|;
   angle = angle + acos(dp);
   he = he.twin.next;
}while(he ≠ vertex.halfedge);

vertex.curvature = 2π − angle;
```

Figure 2-7: Code to compute the *vertex normal* and the *vertex curvature*.

Chapter 3

Concept

This section introduces a software tool that allows designers to copy a feature from one object (the source product) and paste it onto another object (the target product). Moreover, the detail is adapted and incorporated into the geometric context of the target product. An example of cutting a free-form shape from one surface and pasting it into to another is shown in Figure 3-1. Note that the original leaf detail is flat while the pasted leaf detail conforms to the shape of the vase surface onto which it is pasted.

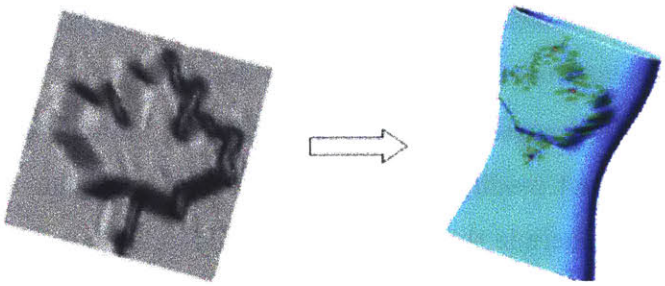


Figure 3-1: Example of transfer of a maple leaf from a flat surface to an oval vase. The leaf assumes the curvature of the vase.

Throughout this section the phrase "geometric context" will be used to designate the shape and texture of a product surface at a given point. The word "feature" and "detail" are used to designate the geometric object that the designer transfers from one surface to another.

3.1 Related Work

3.1.1 Aesthetic Form Synthesis

Work applying computational approaches to aesthetic form synthesis has a long history in architecture. More recently, in the area of product design, pioneering research includes work by: Wallace [23], Knoop [11] and Cagan [3]. This section reviews three categories of shape synthesis techniques: shape grammar, expert system and semantic transformations. These techniques aim towards goals similar to the work described in this thesis –namely to facilitate an industrial designer's form synthesis task during early stages of the product development process. A more complete discussion about shape synthesis is presented by Smyth [15].

1. Shape Grammars

   Introduced by Stiny [17], shape grammars first require one to define rules for the grammar. Forming an explicit set of "grammatical" rules for how to generate object forms is a non-trivial task. Once defined, the grammar can be used to combine different shapes to produce novel designs. Even though this technique produces usable designs, the approach has been limited to relatively regular forms and does not readily support freeform surface design. Successful uses of shape grammars include the generation of building designs [7] and coffeemakers in a particular style [3].

2. Expert Systems

   Wallace [22] used an expert system to automatically generate box-like consumer electronic product layouts and enclosures subject to various types of constraints on the size, the components, etc. (Figure 3-2). Although aesthetic, manufacturing, ergonomic and corporate identity requirements were integrated into the

design, the approach is fundamentally limited by the features available in the parts library and the predefined set of rules.

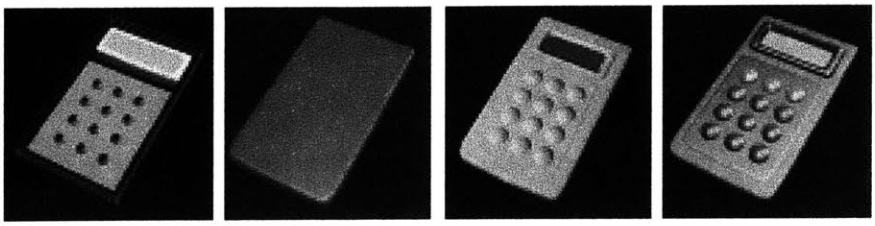


Figure 3-2: Example of automatically generated concept using a rule based system [22].

3. Semantic Transformation

   Form can be manipulated by constructing a mapping between descriptive words and shape transformations. This type of operation is appealing because words are high-level form operators and constitute a common set of descriptors for all participants in the conceptual design process. However, the application of semantic transformations is limited by the complexity of the design and ambiguity of the natural language. Such an approach has been used to analyze the results of consumer surveys and determine relationships between image, shape-regulating words and car styles [9].

While our framework also aims to facilitate the early stage of conceptual design, from a technical standpoint it differs from previous systems. The three preceding approaches represent different methods for mapping between concepts, ideas and shape. In contrast, the method proposed here builds on work related to shape reuse and the Copy-and-Paste editing of freeform models.

3.1.2 Shape Reuse and Copy-and-Paste Editing

The increasing importance of digital modeling in industrial design, and widespread access to 3D scanners, has led to new research on shape reuse in conceptual design. Song [16] and Vergeest [20] fit freeform shape patterns to scanned features. The user can transfer a pattern to a surface in the same fashion he or she would do with a conventional Copy-and-Paste operator. The main drawback of the method is that each pattern has to be predefined and parameterized and, therefore, the designer is limited in his pattern choices.

Wang [24] proposes an explicit pasting mechanism for free form features. The feature is first extracted from the original surface by cutting the contours of the source region. The region is then stitched to the target using an intermediate surface. This approach is suitable for situations where features can be pasted without modification, but it may not be appropriate when the detail requires adaptation to the geometrical context of the target surface. In order to adapt the pasted feature to the target object's shape (i.e., geometrical context) a method categorized by Wang [24] as offset pasting is needed. The method described in this thesis employs a high-field to describe the offset. Figure 3-3 illustrates the difference between explicit and high-field pasting.

In practice, it is often desirable to adapt the pasted feature to the geometrical context of the target region. Biermann [1] describes a multi-resolution framework using surface subdivision that tailors source features to the target surface using a planar parameterization of both the source and the target region. Beirmann defines details as the difference between a finer and coarser resolution levels in the subdivision structure. This definition is powerful because the levels of detail are explicitly stored in the underlying structure of the subdivision representation. The method described in this thesis builds on this work, but uses a different parameterization scheme, a different mesh representation and a different model for computer-user interaction.

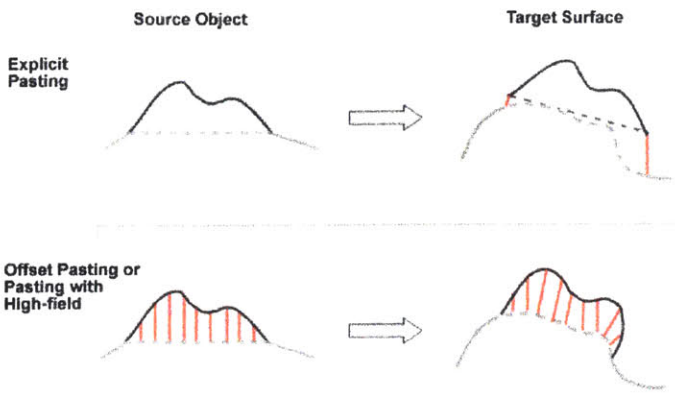


Figure 3-3: Different types of pasting as described by Wang [24].

3.2 Contributions

The work described in this thesis differs from prior efforts in the following ways:

1. The Copy-and-Paste operations can be applied between different geometrical contexts. This means that both the essence of the pasted detail (from the source object) and the nature of target surface are observable after the transformation. A balance is struck between the original shape of the detail to be pasted and the shape of the target surface.

2. The surface editing process is designed to be as natural and intuitive as possible. The tool implemented matches common design vocabulary such as *"I want a corner like this one"* or *"I want a trim line which reminds me of that one"*.

3. Shape exploration and synthesis is encouraged through interactive transformations, such as local deformation of region contours.

Since this concept allows shape reuse between both physical and digital models, the approach may also integrate well with a hybrid physical/digital design cycle [12].

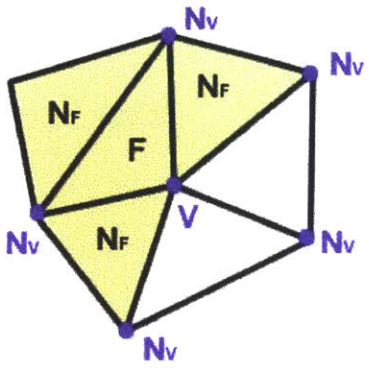


Figure 3-4: In yellow, a face (F) and its neighboring faces (Nf). In blue, a vertex (V) and its neighbors (Nv). The set of the neighboring vertices (Nv) is often referred as the umbrella of (V).

3.2.1 Scope

In Summary, this work addresses how to copy a detail from one freeform surface and paste it onto a different freeform surface. In technical terms this goal can be described as: given a triangular mesh surface with a detail of interest (the source region) and a topologically equivalent mesh onto which we want to import the feature (the target region), extract the detail from the source region and paste it onto the target region with as little distortion as possible between the source and target.

3.3 Algorithm Description

3.3.1 Definition

The system uses a triangular mesh surface representation, meaning that triangular faces and vertices are the basic elements, as shown in Figure 3-4.

From the designer's viewpoint the process is divided in two steps: copy and paste. On the software side the two operations involve: (1) the extraction of the detail, (2)

parameterization and (3) integration of the detail into the target surface. In the following sections, each of these operations is illustrated using an example derived from the Volvo logo.

3.4 Detail extraction

Selection of the source region

The extraction process starts with the selection of the source region. The user draws contour strokes around the area containing the feature of interest. The convex hull of the strokes is used to delimit the source region (Figure 3-5). All triangular faces with at least one vertex inside the selected region are tagged as part of the source region (Figure 3-6). A recursive routine is used to correctly extract the faces inside the source region. Starting from the front-most face enclosed in the source region, all three triangular faces in the face's neighborhood are visited. A geometrical test is performed on the neighboring faces to determine if they are defined inside the source region. This approach is recursively applied to neighboring faces inside the region until all faces have been checked. For simplicity, the current implementation is limited to convex regions, but this is not a fundamental restriction (Figure 3-5).

Base – details separation

We believe that there is no precise characterization of the detail to be extracted – it always depends on the geometrical context of the surface on which it resides. In some cases one might wish to Copy-and-Paste a complete rear end corner from one car to another (explicit Copy-and-Paste), while in another case one may wish to transfer only the sharpness of the corner from one vehicle to the other (offset Copy-and-Paste).

Wang [24] deals with how to address explicit Copy-and-Paste; his objective was to integrally and explicitly transfer a feature with all its details to the target surface.

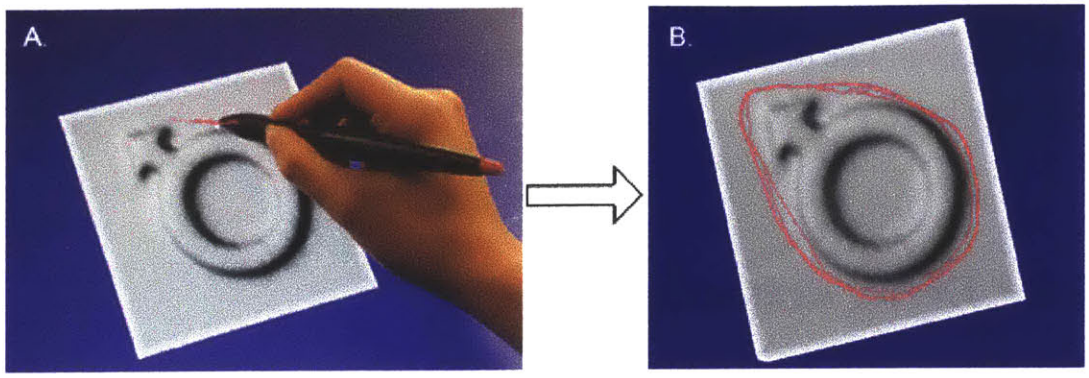


Figure 3-5: A) A user selecting a detail to extract by drawing stokes around the source region. The source detail is based upon a Volvo logo. B) The source selection process is completed, with the convex hull of the stokes defining the source region.

Explicit Copy-and-Paste does not require the separation of the details from the base surface shape of the source geometry. Since we will address high-field copy-and-paste, the problem at this stage is to separate details from the base surface's shape.

We propose two avenues for detail extraction: (1) least squares fitting of a polynomial surface and (2) surface smoothing via signal processing techniques. These two complementary techniques give more freedom in choosing the base surface and thus more flexibility on choosing which details to extract from the source. The algorithm is suitable for copy-and-paste editing of a triangular meshes without subdivision or parametric (e.g. NURBS) representations.

3.4.1 Least squares fitting of a polynomial surface

In this framework, a polynomial surface is fitted to the boundary vertices of the source region. We express the boundary vertices in a local coordinate system and solve the least square problem. This technique is well suited for explicitly extracting details. But, in contrast with explicit pasting, details will be adapted to the target region in the copy process.

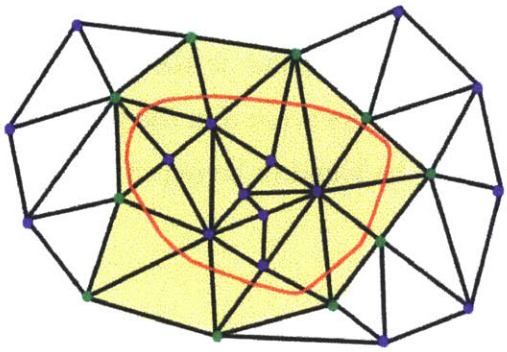


Figure 3-6: The boundary of the source region is shown as a red line. The face defined inside the source region are shown in yellow and the boundary vertices in green.

For example, the following procedure is a step-by-step illustration of how to fit a surface of degree one –a plane– to the boundary vertices using eigenvectors.

i) Express the position of the boundary vertices $\vec{\mathbf{v}}_i$ from their geometrical center $\vec{\mathbf{c}}$ as shown in equations 3.1 and 3.2.

$$\vec{\mathbf{c}} = \left[\sum_{i=0}^{n} \frac{\vec{\mathbf{v}}_i}{n}\right], \quad for\ \forall\ the\ vertices\ v\ on\ the\ boundary \tag{3.1}$$

$$\vec{\mathbf{vc}}_i = \vec{\mathbf{v}}_i - \vec{\mathbf{c}} \tag{3.2}$$

ii) Calculate the covariance matrix M_{cov} and its eigenvectors and eigenvalues following equations 3.3 to 3.6.

$$V = \begin{bmatrix} \vec{\mathbf{vc}}_1 \\ \vec{\mathbf{vc}}_2 \\ \vdots \\ \vec{\mathbf{vc}}_n \end{bmatrix} \tag{3.3}$$

$$M_{cov} = V^T V \tag{3.4}$$

$$E_{vectors} = eigs(M_{cov}) \tag{3.5}$$

$$E_{values} = eig(M_{cov}) \tag{3.6}$$

iii) The normal vector $\vec{\mathbf{n}}$ to the plane is the eigenvector corresponding to the smallest eigenvalue. The parameters a, b, c, d in the parametric equation of the plane $ax + by + cz + d = 0$ can now be found to be (eq. 3.10):

$$a = \vec{\mathbf{n}}_x \tag{3.7}$$

$$b = \vec{\mathbf{n}}_y, \tag{3.8}$$

$$c = \vec{\mathbf{n}}_z \tag{3.9}$$

$$d = -a\vec{\mathbf{c}}_x - b\vec{\mathbf{c}}_y - c\vec{\mathbf{c}}_z \tag{3.10}$$

Once the equation of the plane is calculated, the displacement vector of a vertex in the source region is given as the vector going from the orthogonal projection vertex in the plane to the vertex itself. The calculation of the displacement vector is linear when the polynomial surface is a plane but gets more complex as the degree of the surface increases, for example the vertex could be located at equal distance from two points on the surface, making difficult to make a decision on which displacement vector to choose.

3.4.2 Surface smoothing

Signal processing algorithms defined on triangular meshes [18, 5] are used to improve the quality of surfaces. In the digitizing industry, surface fairing –often refered to as smoothing– is of great interest since it can significantly improve the quality of scanned surfaces by removing noise. Because, from a macroscopic standpoint, surface details can be seen as noise, surface smoothing seems like a particularly attractive technique for extracting sharp details and surface texture.

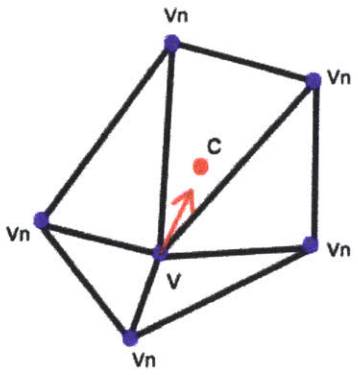


Figure 3-7: An easy way of smoothing a mesh is to move each vertex v towards the geometric center c of the neighboring vertices v_n.

The simplest form of mesh smoothing involve moving each vertex on the mesh towards the geometric center of its neighboring vertices. This technique has the advantage of being very simple to implement but is very computationally expensive. Also, when many iterations are applied, the mesh rapidly shrinks, leading to undesirable shapes.

Explicit, implicit and interactive fairings have been implemented. These techniques are fundamentally similar but algorithmically and practically differ at many levels. Their names, explicit and implicit, come from the type of integration technique used for each case. Explicit fairing, which is basically a formalization of the simple mesh smoothing algorithm described above, allows better control as the source detail smooths and shrinks, but converges slowly for large meshes. For the same level of smoothing, implicit fairing converges much more rapidly, typically by a factor of five to ten. Using implicit fairing, it is also possible to magnify surface characteristics, literally unsmoothing a detail. When used on open surfaces (a surface topologically equivalent to disc), mesh shrinking constitutes the main limitation to the technique. The use of interactive fairing allows designers to better control the choice of which level of detail is to be extracted. The designer locally smooths the surface from which

he wants to extract the detail with a scribbling gesture. The vertices contained in the region of influence are displaced towards the geometric center of neighboring faces.

The principal disadvantage of using smoothing as a technique to extract details is that vertices are moved both in normal and tangential directions. This makes the detail difficult to describe using a high-field. Thus, until now, only poor results have been obtained using this technique.

Displacement Vector

When the feature is extracted, a displacement vector is attributed to each vertex in the source region. This displacement vector is defined as the vector from the vertex after the base-detail separation to the corresponding vertex before the separation operation. The set of the displacement vectors form a displacement field describing the detail, which is known as the high-field (figure 3-8).

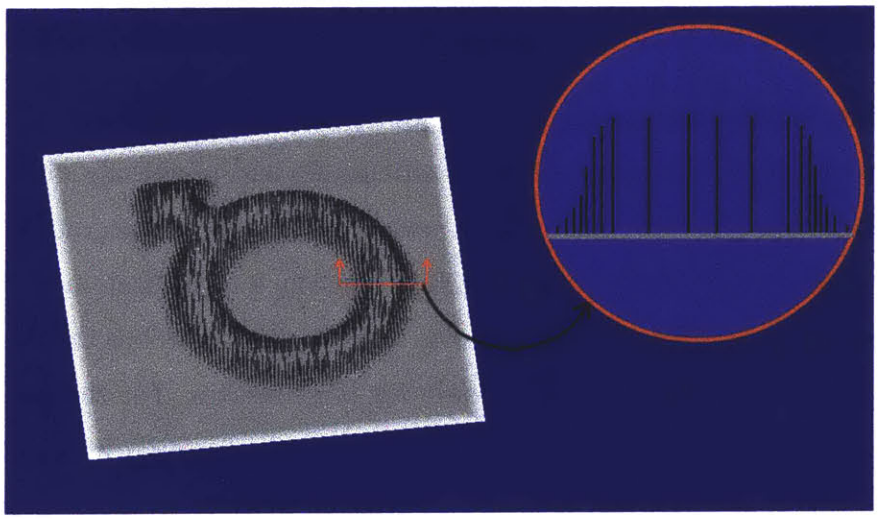


Figure 3-8: Once the detail is extracted from the source region, a high-field characterizes the detail.

At this stage the designer can rescale the displacement vectors in the high-field

either locally or globally. Global scaling is done by uniformly scaling all the vectors by a factor, arbitrarily chosen between 0.5 and 2. Local scaling is accomplished by scribbling over the vertex associated with the displacement vector that the designer wishes to rescale. Local rescaling allows the designer to correct both undesirable details and freely modify the detail (Figure 3-9).

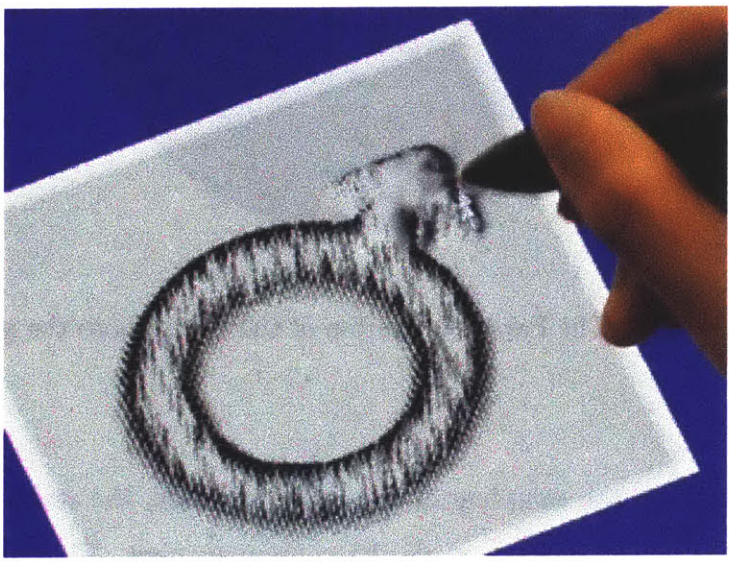


Figure 3-9: The designer can locally rescale the high field in order to remove undesired features. In this case the designer reduces the arrow from the car maker's logo.

3.5 Parameterization to a plane

In order to map the source detail to the target region, a 2D mapping of the 3D triangular mesh must first be computed. Conceptually, this involves unfolding the mesh onto the plane (Figure 3-10). This constraint requires that the source region and the target region are topologically equivalent to disks.

The parameterization should respect three following properties:

1. Affine Transformation Invariant: The result of the parameterization should not be affected by linear transformation since they do not affect the geometry of

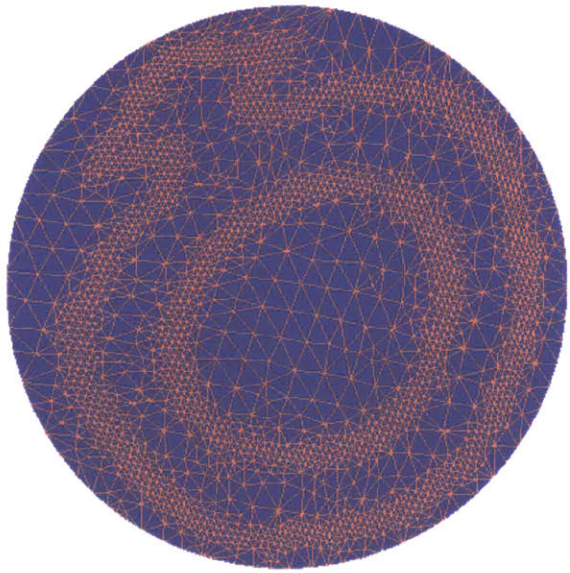


Figure 3-10: The Parameterization of the details onto the plane.

the mesh.

2. Continuity: As the sampling of the mesh increases, the result of the parameterization should tends towards the continuous case. This property ensures consistency between the mesh and its parameterization.

3. Additivity: The addition of vertices onto a given mesh should not affect the parameterization (the parameterization should depend on the surface itself and not on the sampling).

Algorithms for parameterizing meshes have been studied by both mathematicians [13] and computer scientists [8, 4]. The principal applications for such algorithms in computer graphics have traditionally been texture mapping and remeshing. The mathematical formulation corresponds to the minimization of an energy function defined on the mesh. The intrinsic parameterization formulation [4] is used here for its simplicity and concise formulation. The parameterization of the triangular mesh is made by assigning to each 3D vertex a 2D coordinates referring to its position in the

plane (Figure 3-10). A discrete energy gradient is defined for each vertex included in the source region. A linear system is formulated and then solved using an iterative method.

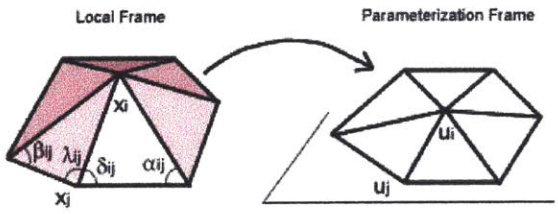


Figure 3-11: The vertex x_i and its umbrella. The coefficients for the parameterization are defined with respect to the neighboring vertices [4].

The key is to calculate how the displacement of each vertex influence the mesh distortion. The distortions depend on two well defined geometric properties of the mesh, the edge length and the angles. Figure 3-12 shows the direction of the area gradient – equivalent to edge length gradient – and the angle gradient for one triangle. These directions correspond to the directions along which the given quantity increases the most.

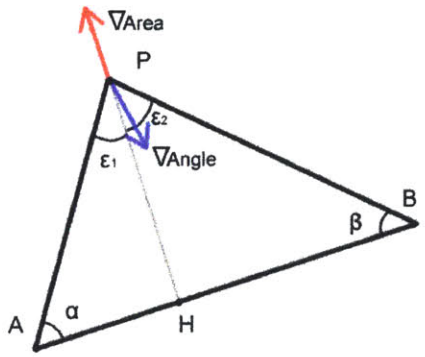


Figure 3-12: A triangular face with its Area and Angle gradients shown.

Using vector algebra we can analytically derive the area gradient. By definition we know that the height of the triangle HP is perpendicular to the base, using this fact we can express the area gradient in function of the vectors $\vec{\mathbf{AP}}$ and $\vec{\mathbf{BP}}$ (Eq. 3.11 to 3.18). The point H, is formally defined as the orthogonal projection of P onto $\vec{\mathbf{AB}}$.

$$
\begin{aligned}
A &= \|\vec{\mathbf{AB}}\|\|\vec{\mathbf{HP}}\| && (3.11)\\
\nabla A &= \nabla(\|AB\|\|HP\|) && (3.12)\\
\nabla A &= \|AB\|\nabla(\|HP\|) && (3.13)\\
\nabla A &= \|AB\|\left(\frac{\vec{\mathbf{HP}}}{\|HP\|}\right) && (3.14)\\
\nabla A &= \frac{1}{\|HP\|}(\|AH\|\vec{\mathbf{HP}} + \|BH\|\vec{\mathbf{HP}}) && (3.15)\\
\nabla A &= \frac{1}{\|HP\|}(\|AH\|(\vec{\mathbf{HP}} + \vec{\mathbf{BH}}) + \|BH\|(\vec{\mathbf{HP}} + \vec{\mathbf{AH}})) && (3.16)\\
\nabla A &= \frac{\|AH\|}{\|HP\|}\vec{\mathbf{BP}} + \frac{\|BH\|}{\|HP\|}\vec{\mathbf{AP}} && (3.17)\\
\nabla A &= (cot(\alpha))\vec{\mathbf{BP}} + (cot(\beta))\vec{\mathbf{AP}} && (3.18)
\end{aligned}
$$

A very similar derivation is used to obtain the angle gradient. The idea for that second derivation arise from splitting the triangle into two right angle triangles as shown on by equations 3.19 to 3.23.

$$
\begin{aligned}
cos(\epsilon_1) &= \frac{\|\vec{\mathbf{PH}}\|}{\|\vec{\mathbf{PA}}\|} && (3.19)\\
\nabla cos(\epsilon_1) &= \nabla\left(\frac{\|\vec{\mathbf{PH}}\|}{\|\vec{\mathbf{PA}}\|}\right) && (3.20)\\
-sin(\epsilon_1)\nabla\epsilon_1 &= \frac{\nabla(\|\vec{\mathbf{PH}}\|)\|\vec{\mathbf{PA}}\| - \nabla(\|\vec{\mathbf{PA}}\|)\|\vec{\mathbf{PH}}\|}{\|\vec{\mathbf{PH}}\|^2} && (3.21)
\end{aligned}
$$

$$\nabla\epsilon_1 = \frac{cot(\alpha)}{\|\vec{\mathbf{PA}}\|^2}\vec{\mathbf{PA}} + \frac{\vec{\mathbf{AB}}}{\|\vec{\mathbf{PH}}\|\|\vec{\mathbf{AB}}\|} \tag{3.22}$$

The gradient $\nabla\epsilon_2$ will cancel out the second term, heading to:

$$\nabla\epsilon = \frac{cot(\alpha)}{\|\vec{\mathbf{PA}}\|^2}\vec{\mathbf{PA}} + \frac{cot(\beta)}{\|\vec{\mathbf{PB}}\|^2}\vec{\mathbf{PB}} \tag{3.23}$$

The energy function should be chosen for desired effects on the aesthetics of the source surface. Eq. 3.24 (conformal mapping) minimizes distortions between the corresponding angles in the original 3D mesh and the 2D parameterization. Using Eq. 3.25 (authalic mapping), the distortion between the edge lengths is minimized. Figure 3-11 shows how the coefficients of the equations are calculated from the triangular mesh.

Since the two formulations correspond to linear systems of the same size they can be combined linearly to form what we call the stiffness matrix of the parameterization (Eq. 3.26). Formally the stiffness matrix is composed of the elements shown on Figure 3.5. Note that the coefficients are applied such that it is consistent with the linear formulation defined on the umbrella of each vertex (Figure 3-11).

The positions of the boundary vertices in the 2D parameter plane ($C^{boundary}$)have to be set since they are used to constrain the linear system. In our framework, the points are mapped to a unit disc. The angular coordinates of the boundary points along the unit disc in the parameterization space is equal to the angular coordinate of the corresponding point in the source region. The angular coordinates are expressed in polar coordinates in the local frame (Figure 3-14). The sparse linear system formed (Eq. 3.26) can be solved using a biconjugate gradient method, which is much faster then a traditional LU decomposition.

$$M_{ij}^{\chi} = \begin{cases} cot(\gamma_{ij}) + cot(\delta_{ij}) / |x_i - x_j|^2 & if\ j \in N(i) \\ -\sum_{k \in N(i)} M_{ij}^{\chi} & if\ i = j \\ 0 & otherwise. \end{cases} \tag{3.24}$$

$$M_{ij}^{A} = \begin{cases} cot(\alpha_{ij}) + cot(\beta_{ij}) & if\ j \in N(i) \\ -\sum_{k \in N(i)} M_{ij}^{A} & if\ i = j \\ 0 & otherwise. \end{cases} \tag{3.25}$$

$$MU = \begin{bmatrix} \lambda M^A + \mu M^{\chi} & \\ 0 & I \end{bmatrix} \begin{bmatrix} U^{internal} \\ U^{boundary} \end{bmatrix} = \begin{bmatrix} 0 \\ C^{boundary} \end{bmatrix} = C \tag{3.26}$$

Figure 3-13: The stiffness matrix of the mesh and the elements it contains.

3.6 Mapping – integration of the details into the target surface

The core of the pasting problem consists of displacing each vertex of the target surface in a way that the details of the source region are correctly replicated in the target region. The first step is to select the target region. Two options are available, one can use a replica of the boundary contours of the source region, or the designer can manually draw a contour on the target region. The manual selection of the target region allows many interesting possibilities in interactive exploration of the shape.

The next step is to parameterize the target region onto a plane and then superimpose the parameterization of the source region (Figure 3-15). Then, using either a point location data structure or a simple brute force algorithm, it is straightforward to find in which triangle of the parameterized source region each vertex of the parameterized target region resides. Once the corresponding triangle is determined for each vertex, its displacement is interpolated using the weighted average of the displacement of the triangle vertices.

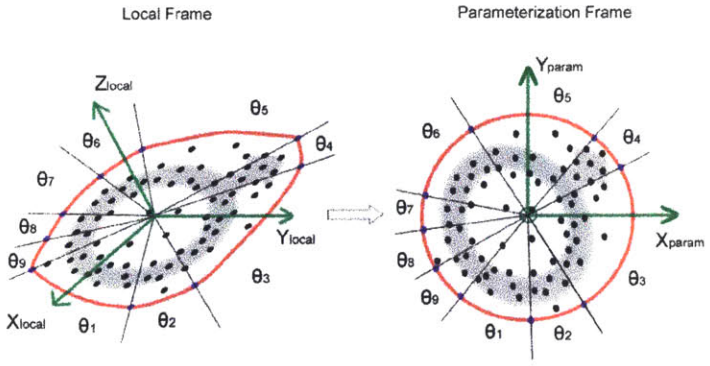


Figure 3-14: The boundary vertices of the source region are placed on the unit circle in such a way that the angle between vertices is kept equal to the corresponding angle in the local frame of the source region.

Figure 3-16 shows the detail integrated into its new geometric context after a Copy-and-Paste operation. Note that the detail has been adapted to the shape of the target surface. When the target region is concave, degeneracy caused by mesh folding may occur (Figure 3-17). This is a common problem [1] and our implementation is not immune to it. Generally, if the difference of curvature between both source and target region is large; the quality of the Copy-and-Paste operation tends to degenerate rapidly.

The main drawback of our implementation is related to distortion in the copied detail. This issue and possible solutions will be discussed more thoroughly in the following section.

3.7 Results

Our method has been implemented on a windows platform using the C programming language, OpenGL and GLUT (OpenGL Utility Toolkit). Our tool can handle common mesh formats (.obj, .noff, etc), allowing the freedom to use meshes from

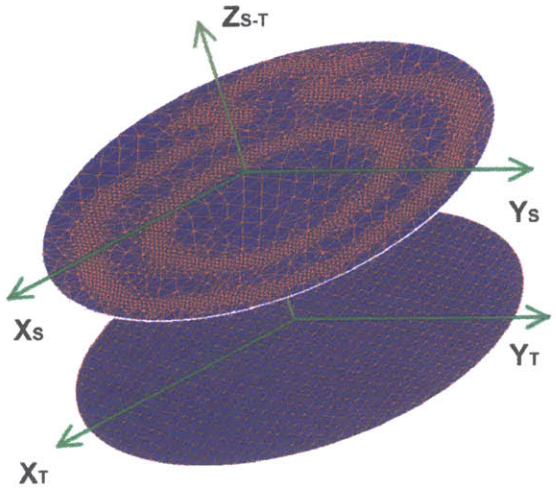


Figure 3-15: The parameterization of the source (S) and target (T) region are superimposed. For each vertex in the target region, the triangle that contains it in the source region is computed and a displacement for the vertex is calculated.

digitizers and from various freeform modelers such as Maya and 3DS Max. We can typically handle triangular meshes containing 10k vertices at interactive rate. Our results demonstrate that we can extract features from one model and successfully paste them onto another model.

A curvature plot of the surface after pasting is a good indicator of how well the Copy-and-Paste performs. Typically, we see more distortions in sharp details. A solution to this problem is to refine the target surface mesh, but this brute force approach can result in overly large meshes and preprocessing times. A solution to this problem is to use subdivision surfaces [2]. By subdividing only the target region mesh it is possible to adequately approximate details of the source region. Another potential solution would be to use feature sensitive remeshing [21] of the target surface. With this method, the vertices of the target region are displaced towards regions of high curvature and tagged to local minima of the curvature field. This could potentially allow the pasting of sharp details without increasing the number of vertices or requir-

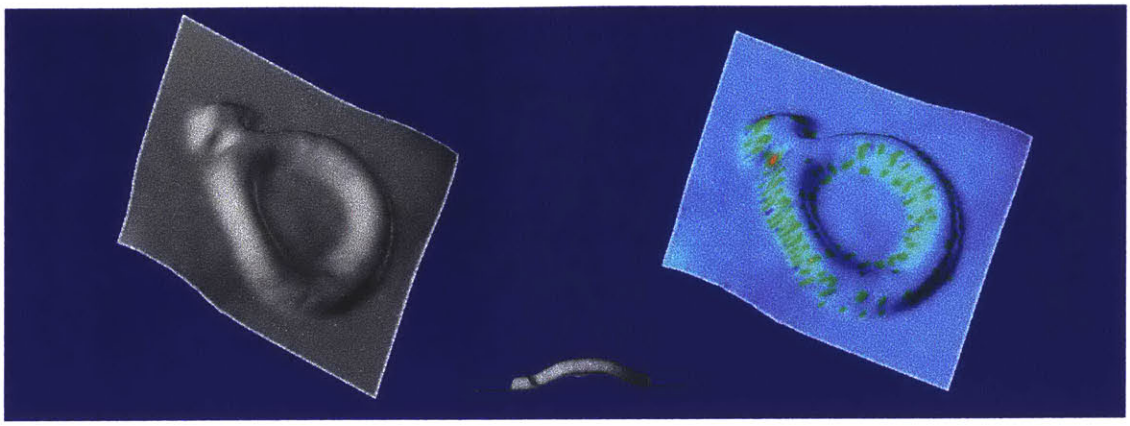


Figure 3-16: The details once pasted on a wavy surface. Notice that the details have adapted to the shape of the target region. The curvature of the detail (right) shown in color highlights the presence of distortions.

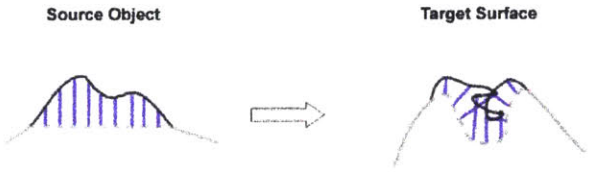


Figure 3-17: A case of degenerate copy-and-paste editing.

ing to subdivisions.

Chapter 4

Application

The driving force behind the work presented in this chapter is to facilitate the early stage of conceptual design by developing more intuitive and intelligent computer applications for the designers. The section describes what we call *example based modeling*, a type of modeling which uses relevant examples of products and processes. First, a simple rule based system for quick 2D and 3D sketching is described. Second, high-level operators based on our 3D Copy-and-Paste tool are introduced as an interactive extension to the interface.

4.1 Motivations

A key point derived from a survey of the leading Computer Aided Industrial Design (CAID) software providers is that industrial designers are under increasing pressure from companies to present innovative concepts in a relatively short time span [14]. Two factors seem to explain this observation:

1. In a context where mass-market consumer products all resemble each other, companies strive to differentiate their products from the competitors through industrial design.

2. A short time to market provides a competitive advantage, as there is a large advantage to being first in a new market.

As an important part of these responsibilities resides with industrial designers, their importance in the design team has grown.

Current CAID systems do not always suit the needs of the user. For example, designers must often provide precise and specific inputs whereas at the conceptual design stage, the designer would like to work with gestural notions. We think that a effective way to solve this problem is through *design by example.*

4.2 Non traditional modeling

By offering a blend of freeform sketching and rule based modeling, the SKETCH system was the first computer application to offer a truly different approach to sketching and design [25]. As the user sketches 2D objects on a tablet, the system infers the third dimension following predefined rules. For example, SKETCH has been successfully used to compose simple scenes with box-like objects such as furniture. The principal drawback is that the system is intrinsically limited by the complexity of the rules and the ability of the designer to take advantage of them.

The Teddy system represents the state-of-the-art in rapid sketching [10]. From a simple interface and a limited set of possible operations, very interesting models can be created and manipulated. But, the most innovative concept in the Teddy system is that most operations do not have to be completely constrained by the user; supplementary constraints are instead inferred by the system based on the context of the operation. Since a lot of the control is lost to make the system simpler, it is difficult to draw realistically looking products in Teddy (Figure fig.carInTeddy), therefore hardly usable in product design.

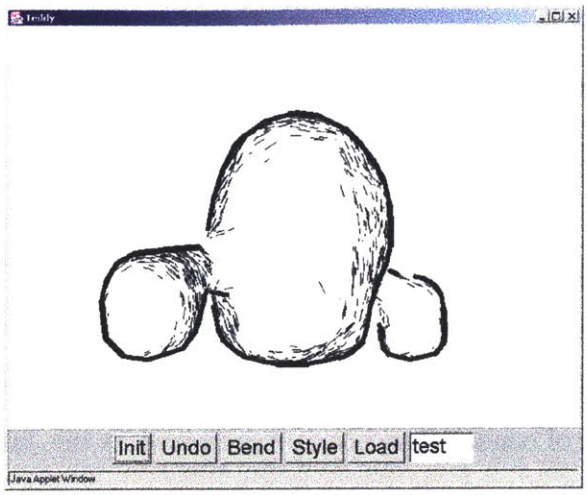


Figure 4-1: The Teddy system and a 3D model created from a car profile. AS the illustration shows, the modeling rules do not suit the purpose of car design.

4.2.1 Rule based system

As mentioned in Chapter 2, Wallace [22, 23] proposed an expert-like system to automatically generate concepts of box like consumer products. Rules and constraints from aesthetic, usability and manufacturing specifications are taken into account by the system. The user defines the style of the product and the features and, then the system automatically generates valid solutions (see Figure 3-2). Similarly the rule based system is limited by the rules and parts library used.

In the proposed solution we would like to integrate the simplicity and intuitiveness of the Teddy system with the power of a product based expert system model. Our model is presented in two parts: the first part describes a 2D and 3D sketching interface which implements heuristics to facilitate its utilization. The second section presents an interactive application for the 3D Copy-and-Paste tool described in chapter 3.

4.3 Example based Modeling

4.3.1 Description of the sketching interface

A system to rapidly design 3D models of concept car is proposed. Using simple heuristics based on a priori knowledge of the product and contextual information, the system rapidly guides the designer towards valid solutions. Basic, but intuitive, 3D modeling operations are implemented and allow subsequent modifications of the design. Contextual information is used to resolve ambiguities between unconstrained gestures. The proof of concept has been programmed in the Java programming language.

2D Sketching. An interface (Figure 4-3) with the look and fell of a sheet of paper is provided and basic controls are available. The sketching interface proposes a set of heuristics that enhance the sketching abilities of the designer and brings him or her towards a valid solution. The first stroke drawn in the system becomes the base stroke. Subsequent strokes modify the base stroke following rules. Examples of heuristics implemented in the sketching interface include (Figure 4-2):

a. Trim the base stroke if the new stroke cut the base stroke close to its end points.

b. Extend the base stroke if the end points are close to each other.

c. Replace part of the base stroke by the new stroke.

d. Erase part of the base stroke when a scribbling gesture is made over it.

The parameters driving these heuristics, for example the radius of the region of influence (Figure 4-2), can be modified accordingly to user preferences.

Transformation of a 2D sketch into a 3D model. When the user signifies to the system that he is satisfied with his sketch (Figure 4-3), the profile is automatically

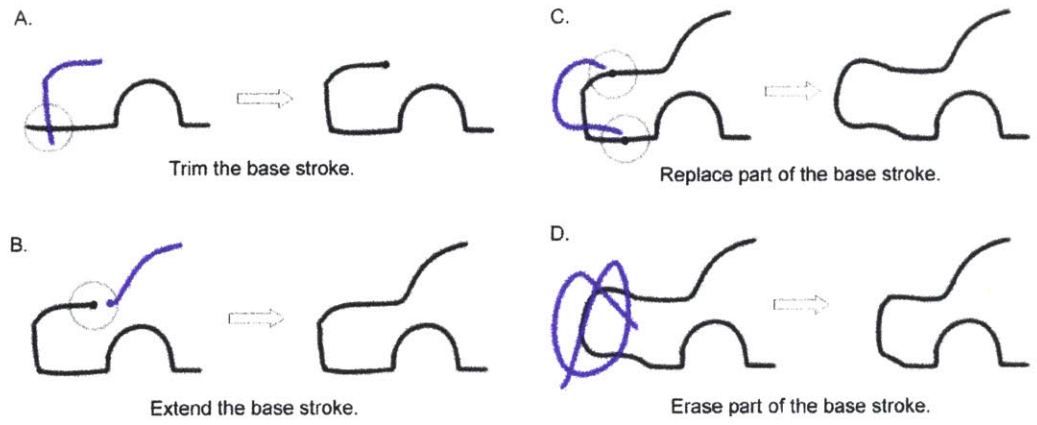


Figure 4-2: Illustration of three heuristics implemented in the sketching interface. The gray circles illustrate the region of influence of the operator.

converted into a 3D model. Because there are an infinite number of 3D models that correspond to a given 2D projection, the conversion form 2D to 3D is challenging. Context and a priori knowledge of the product are used by system to resolve possible 3D models.

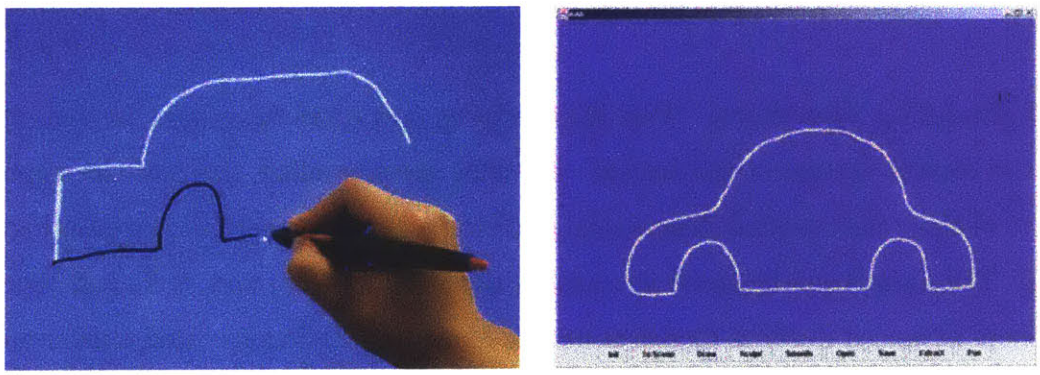


Figure 4-3: The user draws the profile of his car-concept using an electronic tablet. The goal is to define a valid sketch for both the system and the user.

In our application of the car conceptual design, the designer has to first draw the profile of the concept car. Intuitively, to the designer, the 3D models of a car is fairly

obvious from a 2D representation. However, this is not the case for the computer. It is crucial to realize that we are able to infer the third dimension of the car because have a priori knowledge of what a car should look like: this is context. The idea is to give enough context to the program so it can automatically complete models. For example, the current version of the system creates a 3D model from the sketch by extruding the profile and rounding edges (Figure 4-4).This assumption is based on the typical shape of a vehicle.

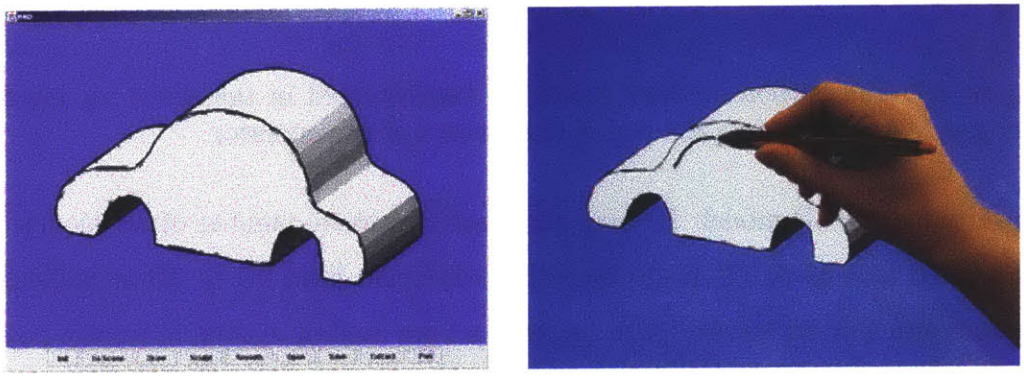


Figure 4-4: Extruded model from the profiles and the user adding a detail on the 3D model.

3D modeling operators. Two 3D modeling operatiors have been implemented in the current version of the system. A *sculpt operator* allow the user the displace vertices along their normal. The second operator is used to smooth the surface (Figure 4-5). The models can be saved in common mesh format (.obj and .noff) and opened in more advanced freeform modelers such as Maya and 3D-Studio. Also, similar mesh formats can be open and modified using the interface.

4.3.2 Identity operators

Even though rule based modeling provides the designer with a quick way to create models and to modify them, the problem related to detailing –adding details and

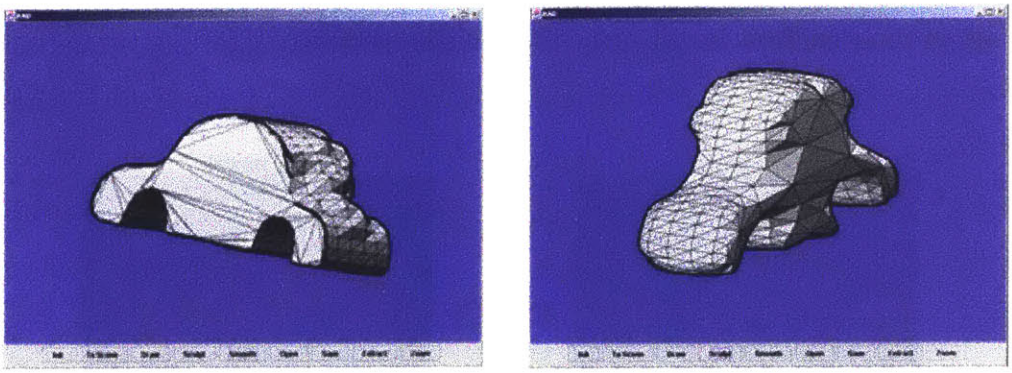


Figure 4-5: Respectively the Sculpt applied on the back of the car model and the smooth operator applied on the entire model. Detailing remains a hard problem.

textures on the model– is not resolved. In the previous chapter, we described a 3D Copy-and-Paste tool that allows the designer to transfer details from one surface to another. A method to interactively use this framework, packaged under the form of *identity operators*, is described here.

The key towards a better CAID system is to make the software understand the product and the process. By giving more information to the system at the sketching step we facilitate detailing and branding operations. We saw how a rule based system can integrate information about the design process and use it to infer actions. For example the system knows how to create a 3D models from the 2D sketch. The concept of an identity operator relies on being able to understanding a product and its principal components. The idea is to match similar components in such a way that a seamless transfer of details between surfaces is made – we basically want to smear on the identity of the example model onto the new model.

The first step of this process is to give to the system some knowledge about the product which is being designed. For example, we can think of dividing the body of a car into three parts: the front, the back and the side. At the 2D sketching step these parts are identified on the profile by the user (Figure 4-6). The transformation

from 2D to 3D uses this information to tag each vertex with the part it belongs to. The set of these surfaces is called the *atlas* of the model.

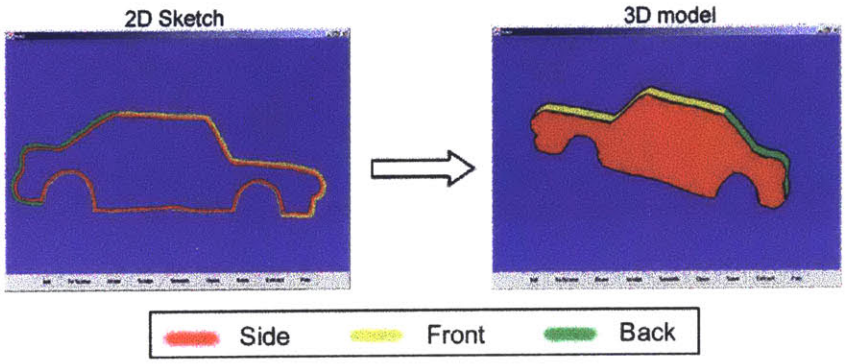


Figure 4-6: When the profile of the car is sketched, the different parts of it are identified in an interactive manner. Here a color scheme represents the different components of the atlas. When the 2D sketch is transformed into a 3D model, the information is used to tag each vertex to a different part.

All the elements of the atlas are topologically equivalent to disks. This allows the parameterization of each component to the unit disc (Figure 4-7) using the intrinsic parameterization scheme presented in the chapter 3. Each car model can be thought as a set containing the specific geometric representation of the model and its related part atlas.

In the *example-based modeling* framework, any such model –geometric representation and atlas– defines an operator that can be used for the design of new models. Figure 4-8 shows how a common parametrization of the same part on different car models can facilitate the transfer of design knowledge from one model to an other.

We can imagine that the designer could use this technique to give an identity to a new car model by transferring details from an other model. For example, by scribbling on the surface the designer can apply the identity from a previously selected car model to a design in the same fashion he might apply colors. We can imagine that a digitized model of a Mercedes could be decomposed and parametrize in an atlas that could be subsequently use as a luxury operator or details from a Volvo model could

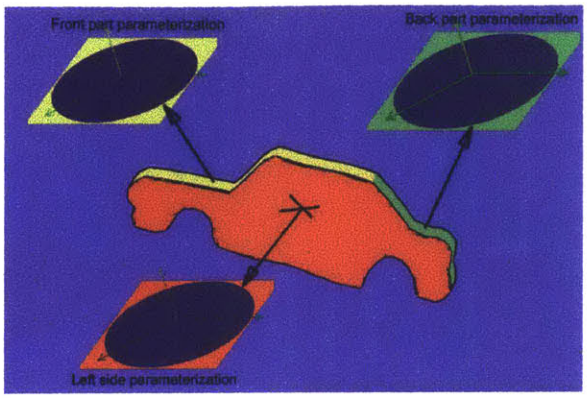


Figure 4-7: Each part of the model are parameterized to a consistent geometric space – in this case a unit disc.

be used to define a security operator.

Selecting and applying the identity – character or a brand – becomes as simple as applying a color. Another nice feature of this approach is that it is grounded in the way the designers think about forms and shapes. It becomes possible for a designer, through the simple click of a button, to transform his or her model with a "I want my model to remind me of this one" operator.

The example produced in this section focuses on car styling and conceptual design, but the proposed approach can be applied to any product or family of product. The only requirement is to be able to identify corresponding parts in a group of products.

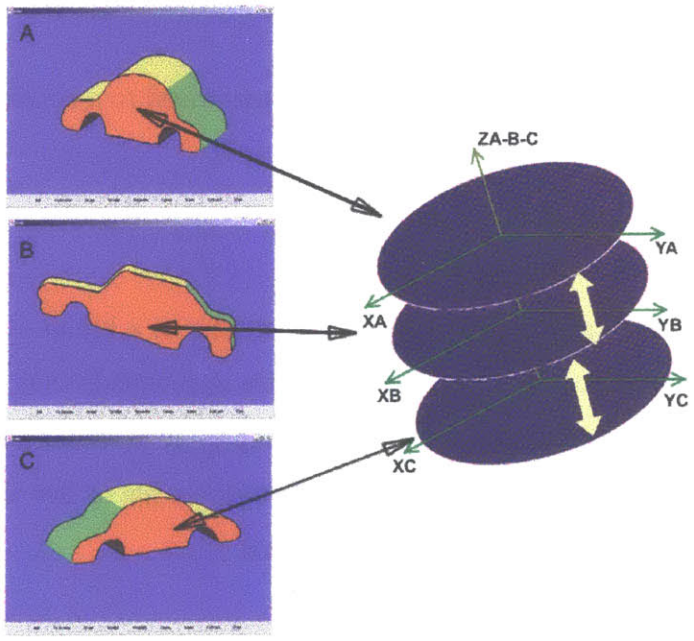


Figure 4-8: The corresponding parts on different car models are parametrized and arrange in a way that allows an easy transfer of details from one to the other. For example, if the designer is working on model A, he can select an operator that would allow transfer of details from model B through the parameterization scheme.

Chapter 5

Conclusion and Future Work

This thesis presents a different model for Computer Aided Industrial Design. A Copy-and-Paste of 3D freeform surfaces application represents the basis of our concept. This modeling tool is integrated, in a second step, into a higher-level application that uses contextual information and examples to facilitate design tasks. This last application presents *example based modeling*, a new concept introduced in chapter 4.

The goal of this work is to develop computer tools and concepts that facilitates conceptual design. The principal motivation is the increasing need to speed up the work of industrial designer. Conceptual flaws in the existing CAID systems have also been pointed out as a motivation to this work. We propose a framework in which shape and form vocabularies correspond to equivalent operators in the computer system.

5.1 Retrospective

3D Copy-and-Paste editing. A tool to Copy-and-Paste details between free form triangular mesh surfaces has been presented. From a design viewpoint, the operation is an intuitive two step process: copy then paste. Manual selection of the detail to be copied, in addition to two techniques for separating the base surface from the detail are proposed. Building on previous work a novel parameterization technique

is used to map both source and target surfaces to a neutral circular planar area. Finally the high-field obtained from the extraction procedure is incorporated into the target surface. This framework is shown to be suitable for transferring design knowledge from previous surface models into new surface models. When integrated into an industrial design cycle, the approach may facilitate editing and exploration of free form surfaces, providing a mechanism for transferring brand identity elements between product forms.

Example based modeling. An interface for 2D and 3D sketching has been implemented. The sketching interface implements a rule based system which allows designers to quickly create and modify 3D models. The concept of *example based modeling* is introduced as a way to seamlessly transfer shapes and design knowledge from one design to another. The *example based modeling* framework implements the 3D Copy-and-Paste tool to create new types of operators based on existing models. Supplementary knowledge about about the product is provided to the system at the sketching step. Using this information, the system is able to infer high-level operations based on similar product example. For example, security or luxury operators can be implemented based on existing product, such as a Volvo and a Mercedes. This high-level operator can be applied to new models in the same way color is normally applied to a model. We called these newly defined operators "Identity operators" because they ultimately allows the designer to smear the identity of the example model onto its design intent.

5.2 Future work

From the design perspective there are three steps towards a functional *example based modeling* software:

1. Integrate the 3D Copy-and-Paste tool into the design environment. Improve the transfer of sharp details and reduce distortions of the pasted details caused

by mesh resolution issues.

2. Improve and refine the heuristics that form the rule based system governing the sketching interface. A user study involving designers should also take place in order to carefully understand the way they think about forms and shapes.

3. Implement a simple way to input product and process knowledge into the system that would not add undesirable overhead to the process.

From the programming standpoint there are number of possible performance improvements.

- A object oriented structure would simplify the code and certainly improve performance of the Copy-and-Paste tool. For example the C++ programming language should be used instead of the C language.

- More efficient use of the OpenGL API would speed up the execution.

- Better optimization of the triangulation would result in improved rendering and more efficient modeling operators.

5.2.1 Final words

The concept of *example based modeling* has yet to be implemented and tested to asses its performance. The system is not meant to replace the designers natural abilities, but to speed up their work in the concept generation step by allowing a much easier way to transfer and reuse design knowledge. We think that building a program that *"understands"* the user intent is the key to a more effective modeling tool.

Product design is not at all a mathematical language. The main purpose of this work was to look at computer aided design by thinking about shapes and forms; what they remind us of or feel like, etc. The way people build models should corresponds

to the way the think about them.

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