Chapter 5. Shape Reverse Engineering

Segmentation and Surface Fitting in Reverse Engineering

Keynote Paper

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Abstract: After a general overview on reverse engineering, various techniques to segment point clouds, which represent 'regular' or 'free-form' objects are described. More details are given on the so-called functional decomposition approach, which is based on the logical separation of primary surfaces and feature elements.

1. REVERSE ENGINEERING

Reverse engineering of geometric shapes is a rapidly evolving discipline [11], [14]. While conventional engineering transforms engineering concepts and models into real parts, in reverse engineering real parts are transformed into engineering models and concepts. Reverse engineering typically starts with measuring an existing object so that a computer representation of a surface or solid can be deduced in order to exploit the advantages of CAD/CAM technologies, including the modification of previous designs, analysis, inspection, NC manufacturing and so on.

There are several application areas of reverse engineering. It is often necessary to produce a copy of a part, when no original drawings or documentation are available. In other cases we may want to re-engineer an existing part in order to construct a new improved product. Computer models based on real-scale wood or clay models are needed in areas where aesthetic design is particularly important such as in the automobile industry. Another important area is to generate custom fits to surfaces of the human body, for mating parts such as helmets, space suits or prostheses.

The ultimate goal of reverse engineering systems is to realise an *intelligent 3D scanner*. This means that based on discrete point clouds such CAD models need to be generated, which represent the original parts not only in "some" approximate way, but clearly reflect the underlying structure of these objects. In spite of encouraging partial results, to create a complete, consistent and high quality CAD model in a fully automatic manner is still a difficult and complex task with several unsolved subproblems.

The process of reverse engineering can be divided into four phases [14]. After *data acquisition*, *pre-processing* of the data set is required for filtering noise, establishing connectivity between adjacent points, reducing redundancy and merging point clouds taken from multiple views. In the third phase the point clouds are *segmented* and surfaces are *fitted* to approximate these separated subsets. The process is concluded by the actual *geometric model creation*, i.e. integrating the individual surface components into a consistent boundary representation model.

This presentation mainly deals with segmentation, which is tightly coupled with surface fitting. After reviewing various approaches, particular solutions are discussed in details.

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Objects are characterized according to the type of their bounding surfaces. For *regular objects*, most of the segmenting process can be performed in an automatic way, if certain assumptions are satisfied. For *free-form shapes* interactive assistance is generally recommended for high quality results. The basic principles of the so-called *functional decomposition* method will be presented in more details emphasizing two important aspects: using ignore areas and constrained surface fitting of free-form features.

2. A HIERARCHY OF BOUNDING SURFACE ELEMENTS

Having *a priori information* about the type of the bounding surfaces of the object is crucial, since different segmentation methods and surface fitting algorithms need to be applied in different situations. This is why it is important to characterize the given objects from a geometric point of view.

Typically objects are bounded by relatively large *primary* surfaces. The primary surfaces are often connected by smooth *transition surfaces*, such as blends or free-form steps. Other types of *feature elements*, such as free-form slots or pockets, also often occur. These feature elements are well-defined from functional or geometric point of view and can be characterized by a few parameters and their relationship to the involved primary surfaces. A possible classification of features is given in [6]; on the recovery of edge blends and free-form features see [5] and [10], respectively.

Returning to the hierarchy of primary surfaces, we restrict our interest to surface types which are used as standard representations in the majority of CAD/CAM systems. We start with *simple surfaces*, which have both implicit and parametric representations and conclude with more general piecewise parametric surface representations. Simple surfaces - planes, natural quadrics and tori - are the most preferred in mechanical engineering practice. They have a representation in terms of a few geometrically meaningful parameters which makes segmentation and surface fitting relatively easy.

Considering more general free-form surface elements, it is worth considering first *translational and rotational sweeps*, characterized by some profile curve and a sweeping direction or an axis of rotation, respectively. This classification can be extended to more general sweeps. Our most general surface class is that of *composite free-form surfaces* where no geometric or topological regularity can be recognized. Such a composite surface may be a collection of patches or possibly trimmed patches where internal smoothness is maintained across the boundaries.

The above classification will help to formalize our basic assumptions to segment various objects.

3. SEGMENTATION AND SURFACE FITTING

In this section we identify the problems of segmentation in general, see also [1] and [13]. The tasks to be solved at this stage of reconstruction are

(i) to logically divide the original point set into subsets, one for each constituting surface, so that each subset contains just those points sampled from the particular surface,

(ii) to decide to what type of surface each subset of points belongs (e.g. planar, cylindrical, rotational, free-form),

(iii) and to find that surface of the given type, which is the best fit to those points in the given subset.

It should be clearly noted that in practice these tasks cannot be carried out in the sequential order given above, since to decide whether certain points belong to a given subset requires some measure of how well they match the underlying surface the points may represent. At each phase of the segmentation process there is always a given hypothesis according to which a best fit surface is constructed, this is why segmentation and surface fitting can hardly be separated. Typically backtracking, iterative, or probabilistic methods need to be used to finally converge to a consistent answer.

A standard approach coming from Computer Vision is *region growing* – see for example Leonardis et al [7] and Sapidis et al [12]. First, certain seed points are selected and based on estimated differential geometry quantities local surface approximations are made around them. These local surfaces are fattened until further consistent data points can be found in the surroundings and finally regions obtained are united to get larger surface portions.

4. SEGMENTING REGULAR OBJECTS

Let us define the class of regular objects as objects bounded exclusively by primitive surface types of planes, spheres, cylinders, cones and tori. Let us also assume that the width of the connecting blending surfaces is relatively small. Due to the given finite number of surface types which all have canonical representation, segmenting this sort of objects without user interaction seems possible.

Region growing is often applied to segmenting regular objects. Most approaches are based on $z = f(x,y)$ type surfaces or computing algebraic distances of implicit equations. This may result in unsatisfactory surface approximations. An improved solution using quasi-geometric distances was recently suggested by Lukács et al [9].

As an alternative, here we propose a non-iterative procedure called *direct segmentation* [15], which is based on combining traditional algorithms with new ones. We assume that for each data point a good normal vector can be estimated based on the surrounding points. Methods for separating regions by planarity filtering, identifying clusters and circles on the Gaussian sphere and applying special filters, which separate point sets according to their dimensionality are discussed in details in [15]. Special emphasis is put on recognizing translational and rotational sweeps. Pottmann and Randrup [9] recently suggested a technique to find rotational axes. Using normal vector estimates as well, this method perfectly fits to the direct segmentation concept; thus it is possible to detect tori and more general rotational sweeps by contours composed of line segments and circular arcs.

5. SEGMENTATION STRATEGIES FOR FREE-FORM SHAPES

Let us assume that we have a composite free-form object, which is smooth everywhere internally and bounded by edge loops. These edges may be partly or entirely the boundaries of some underlying patches or they may also be trimming curves cutting across the patch structure. Such trimming curves may have been determined by higher level operations such as intersections, Boolean operations or blending. For example, we may want to reconstruct just a large, single shape with high geometric complexity or we may wish to deal with a composite free-form surface, which has already been separated from the rest of a solid object.

The most widely used parametric surfaces, such as Bézier patches and NURBS surfaces, map a rectangular parametric domain into 3D, resulting in surface patches with four boundary curves, but many complex free-form shapes cannot be represented by a single surface. A composition of several surface pieces is required while maintaining appropriate continuity between the constituent elements. The key issue here is how to do this additional free-form segmentation, i.e. how to find appropriate internal boundaries, which delineate such local regions, and which are representable by single surface patches.

Four different approaches for free-form segmentation have been identified in [14]:

(i) global approximating surfaces
(ii) arbitrary topology surfaces based on decimated triangular meshes
(iii) curve network based surfaces
(iv) functionally decomposed surfaces

In the first two approaches the surfaces are created practically without user interaction, and no attempt is made to somehow recognize the underlying design structure. This may have the consequence that the generated surfaces will not meet the high quality requirements, which are needed for objects, such as car bodies. The third or fourth approaches are based on some sort of user assistance, and it is evident that in this way much better surface qualities can be assured. While curve network based segmentation seems to be the most widely applied approach in the current industrial practice, functional decomposition methods gain more and more attention. Instead of explicitly drawing a curve network over the point cloud, a high-level, abstract description of the object and a rough control network drives the reconstruction procedure, as explained in the next section.

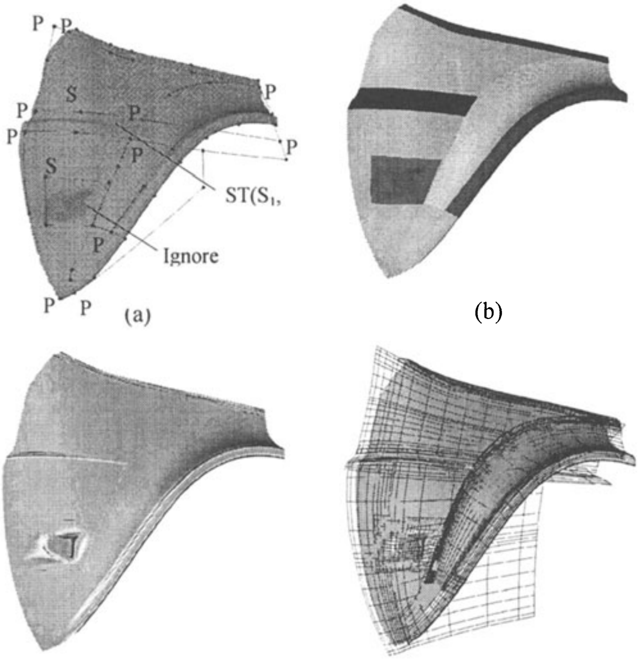
6. FUNCTIONAL DECOMPOSITION AND FEATURE FITTING

The curve network based method has several deficiencies. First of all, it is very hard to define an accurate curve network over the point cloud, particularly to determine the exact position of smooth edges. Minor mistakes here may lead to the inclusion of wrong points, which may create problems at surface fitting. An example is to locate the trimlines of a blend: to find the right boundaries is almost impossible. Another problem is that the curve network approach may create artificial boundaries between regions, which otherwise would belong together; thus a global fairing of the functionally common regions can hardly be performed. To enforce a rectangular topology to a shape with irregular topology is also not an obvious issue.

The functional decomposition method overcomes most of the difficulties mentioned above. Here we also use a curve network for supporting segmentation, but with a fundamentally different role than before. It is assumed, that the user has a functional understanding of the shape involved, and there exists an abstract model, where the *hierarchy* of the primary surfaces and the dependent features are clearly identified. Here the curve network is used to define not the exact subdividing boundaries, rather to roughly and safely identify regions of points, which belong to one particular surface from geometric or functional points of view. These surfaces can later be extended, intersected and smoothed as one would perform these operations in a "non-reverse" CAD environment. Where the positioning of internal boundaries is critical, it will be performed by the fitting algorithms, in a way, that the original topological structure suggested by the user is kept. There is no need to define rectangular surface elements, however, the desired four-sided *frame* of the patches are advised to be defined. The functional decomposition method creates all primary surfaces in complete, extendable form, which have served or may have served for defining the object. The dependent feature elements are generated as being constrained to join the neighbouring primary surfaces smoothly.

The above concept is better explained by an example. In Figure 1/a a car body panel is shown. We deal with a subpart of the object. S1 is a primary surface bounded by the P0-P1-P8-P10-P0 loop. It can be seen that in the middle there is a special feature element; the points belonging to it will be excluded when we fit the large primary surface for S1. This is the so-called *ignore area*, which needs to be supplemented to the boundary information, when the surface S1 is fitted. In this way the original surface can be reconstructed with the best possible quality, and later the feature with elements of high curvature can be added. Another 5-sided free-form face is defined by the loop P2-P4-P5-P7-P2. This loop is to define roughly the internal trimming, while the loop P2-P3-P5-P6-P2 is to identify roughly the frame orientation of the initial surface, which is used to approximate the points within the internal loop. The bottom primary surface is denoted by S2. Note, the main role of the control network was to roughly bound the point regions, which belong to the individual surface components. Assuming that the surface representations for S1 and S2 have already been created, now it is possible to reconstruct a free-form step feature (ST), which is clearly dependent on S1 and S2. Figure 1/b shows the logical structure of the regions created. Figure 1/c shows the final model, which is a collection of trimmed NURBS patches: rendering shows the colours by the mean curvature. Finally, Figure 1/d shows not only the trimmed patches, but also the control nets of the constituting surface elements without trimming.

Note: the accuracy of the approximation is less than 0.1mm.



(a) (b)

(c) (d)

Figure 1: (a) curve network , (b) regions, (c) trimmed patches, (d) untrimmed patches

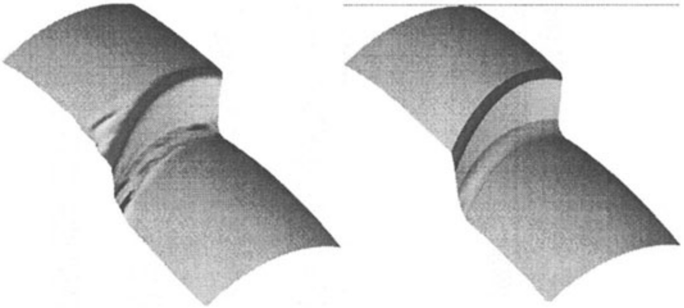


Figure 2: (a) global surface approximation, (b) applying functional decomposition

Finally, we briefly present the concept of feature fitting. As was indicated before, it is possible to produce high quality results, if instead of applying general surface fitting algorithms, special algorithms are used, which in accordance with the characterization of the feature applies special constraints in the surface fitting procedure. Constraints include the smoothness conditions to neighbouring primary surfaces and a priori knowledge about the feature type. For example, a variable radius rolling ball blend will be characterized by a fair spine curve, or a free-form step feature will be defined as sweeping a profile made up of two varying circular arcs and a varying straight segment between them. These constraints help to reconstruct the features exactly in the way as they are defined. Although, one obvious disadvantage is that for each abstract feature type a special fitting algorithm needs to be developed. More details on feature fitting can be found in [10]. As an example, a step feature is shown in Figure 2. Taking the given point cloud and fitting a single surface globally would lead to a surface, whose mean curvature map is shown in Figure 2/a. This indicates problems of approximating with large spline surfaces with relatively small, highly curved areas in the interior. By means of the functional decomposition method, using the two related primary surfaces, a much better surface representation can be obtained, as shown in Figure 2/b.

7. CONCLUSION

Segmentation and surface fitting are crucial elements in reverse engineering geometric shapes. Various approaches to segment regular and free-form objects have been reviewed. Finally, a new paradigm of applying functional decomposition for free-form shapes has been presented. This is a special region driven approach, where surface fitting with ignore areas and techniques to reproduce special feature elements are applied.

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