Faithful segmentation algorithms in digital shape reconstruction

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Summary of the Ph.D. dissertation

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1 Introduction

Digital shape reconstruction (formerly known as reverse engineering) is a modern research discipline that has significantly evolved over the last 10–15 years and is the basis of numerous important engineering and medical applications [Várady et al., 1997, Marks, 2005]. From a scientific point of view, its theory mostly belongs to the field of computer science, more precisely, computer-aided geometric design (CAGD), which deals with the design and representation of three-dimensional objects and related algorithms.

1.1 Digital shape reconstruction

Digital shape reconstruction deals with the conversion of a measured point cloud sampled from the surface of an existing physical object into a computer model that can be processed by a CAD system. In some sense this is the inverse operation of the traditional computer-aided design and manufacturing (CAD/CAM), where a computer model is converted into a physical object.

There are numerous applications of digital shape reconstruction. For example, archiving of an existing object, that is, creating an identical/slightly modified duplicate, when the original plans or computer models are not available requires digital shape reconstruction. Other examples are medical applications, where the goal is to create customized items that are perfectly matched to the idiosyncratic features of patients (prostheses, dental implants). Another important demand arises when objects that were not created by the means of computer systems need to be processed/redesigned. Nowadays – and even in the next decade, according to some experts in automotive industry – car bodies are designed by artist using clay models. Obviously, when computer models are created from the clay designs, not only numerical accuracy is an important issue, but along with high quality surfaces (fair, uniform curvature distribution) the surface structure, including the design intent has to be properly reproduced.

An ideal reverse engineering system should create a faithful computer model and should recognize the original structure and most likely design intent. This is very difficult, often even an experienced engineer can hardly decide which one of the possible structures is the most advantageous for further use. Therefore, shape reconstruction can be seen as an artificial intelligence problem. The reproduction of the original structure would facilitate further operations on the object; in its absence the object has to be redesigned from scratch, which is more expensive and time consuming.

Despite the importance of reverse engineering, commercial systems available during the time of this research are still far behind from expectations. Some of them totally ignore the original underlying structure of the object, while others require additional user input provided by engineering experts in a tedious and time-consuming way.
Figure 1: The process of reverse engineering
1.2 The process of reverse engineering

The process of reverse engineering generally consists of four main steps (see Figure 1): sampling, triangulation, segmentation and surface fitting.

In the phase of sampling, the physical object is measured and the coordinates of three dimensional points are recorded. Nowadays a large variety of data acquisition technologies exists, like laser scanning or touch probing, which mainly differ in the speed and accuracy of acquisition. Mechanical techniques allow higher accuracy, while laser based optical devices are able to capture several thousands of points per second.

The goal of triangulation is to convert the sampled point cloud into a discrete, polygonal mesh surface. Point clouds captured from different viewpoints are first merged, aligned and transformed into a canonical coordinate system. After some noise reduction, the local neighborhood relations are detected and a topologically consistent mesh is generated. Optionally, a decimation step is performed to reduce the amount of data.

Segmentation is the step in which the triangles corresponding to the same surfaces are grouped into regions, and their dependency relations are determined. This is the most crucial step of the process with respect to the final model. The problem lies in the fact that at this stage the type and the extent of the surfaces are unknown. The regions created by the segmentation determine the point set used later for computing the surfaces, as well as the face topology of the final model. Misclassified points/triangles result in bad surface quality, wavy surfaces and uneven curvature distribution. In extreme situations the adjacent faces of the model might be unstitchable. A detailed overview of the literature is found in the next section.

During surface fitting the type of each individual region is determined and its points are approximated by a surface of that type. The surfaces are created according to the dependency relations determined during the segmentation phase, so that adjacent faces can be stitched. The model is then finalized by combined beautification and fairing of the surfaces, and is thereafter ready for further processing by a CAD/CAM systems.
2 Related work and background

2.1 Approaches for digital shape reconstruction

All four approaches for digital shape reconstruction presented below [Várady, 2008] use polygonal mesh input to build CAD model. At the same time, polygonal representation itself is suitable for different applications, where there is no need for high quality surfaces structured according to the original design intent (for example, visualization, finite element analysis, rapid prototyping, modeling organic objects).

(a) Quadrilateral patch layout
(b) Functional decomposition

Figure 2: Different digital shape reconstruction approaches

2.1.1 Quadrilateral patch layouts

Tiling is an automatic surfacing approach where the polygonal surface of the object is partitioned by its main characteristic curves and additional subdividing curves into quadrilateral (four-sided) patches [Eck & Hoppe, 1996] (Figure 2.(a)). The individual regions are then approximated by NURBS patches and $G^1$ continuity is enforced between adjacent surfaces.

The strength of this method is that the procedure is practically automated and minimal user interaction is needed. The corresponding boundary curves of adjacent patches are numerically identical, so the model is watertight.

The main weakness of this representation is due to the usage of quadrilateral patches. The faces of engineering parts are typically non-four-sided, often analytical surfaces. Approximating these with multiple NURBS patches results in low surface quality. Figure 3 illustrates that the alignment of iso-parameter lines and principal curvature lines of a surface results in significantly better curvature distribution.
2.1.2 Manually created segmenting curve network

Manual segmentation is still a classical approach of digital shape reconstruction, which means that users interactively specify the surface boundaries. The exact positioning of the boundaries is critical, as misplaced curves may destroy the surface quality. The surface is decomposed into a set of – mostly, but not necessarily quadrilateral – regions, which are then approximated by surfaces enforcing different continuity conditions at their boundaries. Semi-automatic tools are available to make manual operations faster, however, the reconstruction process is time consuming, iterative process. This was one of the most popular methods among the former industrial approaches, as other methods failed to create curve networks of desired quality.

Manual segmentation requires laborious efforts, but users get models that perfectly match their conception and fully recapture the original design intent. The most advanced reconstruction systems offer fairing/beautifying tools as well. The reconstruction time for an object might take days (or even weeks), but perfect, so-called class A surfaces of immaculate reflection and curvature maps are created, which is necessary for certain applications (e.g., car bodies).

In contrast to the reconstruction of free-form surfaces, manual segmentation is hardly applicable to prismatic parts, which consist of a large number of simple, analytic faces merged by various CAD operations. The manual segmentation of such complex topological structures is impossible in practice.
2.1.3 CAD models redesigned over meshes

The process of reconstructing CAD models over meshes is very similar for the constructional CAD approach: a series of CAD operations is performed. However, the basic geometrical elements are created using the triangulated surface. As a simple analogy, imagine a hand-sketched drawing being redrawn over the sketch using compasses and rulers.

The advantage of the approach is that it follows the standard CAD process: first, volumetric CAD operations are used to define basic building elements, which are then combined by Boolean operations, and finally, sharp intersection edges are blended. The definition of basic elements is based on triangulation constructed from the measured data. As a result of the process, beside the CAD model its full CAD history is also available, which can be replayed to create similar models with different parameters.

A disadvantage of the redesign is that the type of geometric elements, the Boolean operations and all further CAD operations have to be specified by the user one-by-one. This can often be very time consuming, and also makes the whole process error-prone.

2.1.4 Functional decomposition

The goal of functional decomposition is to recapture the original or most likely design intent of the model [Várady et al., 1997, 7], see Figure 2.(b).

The recognition of the design intent, that is, which original surfaces and modeling operations have been applied to construct the object, is a hard problem. Often, even an expert cannot confidently tell the exact sequence of operations, or select the best alternative among a few possible options. Functional decomposition is the perfect solution from engineering point of view, but different problems arise. First, without user interaction it is difficult (or even impossible) to determine the CAD operations that were applied. Moreover, surface fitting is also hard since the extended original surfaces have to be reconstructed based on their trimmed parts. Further issues arise as the adjacent surfaces are connected at their (internal) trim curves instead of their original boundaries, thus instead of exact continuity, only numerical continuity within a tolerance can be guaranteed.

The advantage of functional decomposition is that it creates a complete and consistent boundary representation model consisting of faces defined by larger surfaces and trimming loops. These models are more compact than triangulated meshes or quadrilateral patch layouts. Due to the availability of the (most likely) design intent, the model can be modified and edited (e.g., changing blending radius, fine-tuning primary surfaces).
### Table 1: Comparison of digital reconstruction approaches

<table>
<thead>
<tr>
<th></th>
<th>surface quality</th>
<th>amount of manual work</th>
<th>design intent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>polygonal meshes</strong></td>
<td>discrete</td>
<td>moderate</td>
<td>no</td>
</tr>
<tr>
<td><strong>quadrilateral patch layouts</strong></td>
<td>medium</td>
<td>minimal</td>
<td>no</td>
</tr>
<tr>
<td><strong>manual segmentation</strong></td>
<td>very high</td>
<td>very high</td>
<td>yes</td>
</tr>
<tr>
<td><strong>redesign over the mesh</strong></td>
<td>high</td>
<td>high</td>
<td>yes</td>
</tr>
<tr>
<td><strong>functional decomposition</strong></td>
<td>high</td>
<td>low</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### 2.2 Partitioning to mesh into primary regions

Segmentation can be seen as the recognition of the original or most likely topological structure of an object. Segmentation is a very hard problem; both the structure and the geometrical elements are unknown and can only be inferred indirectly, based on measured points.

The general segmentation methods can be classified into two groups. *Edge based* methods detect points located in the vicinity of surface boundaries and construct the regions corresponding to the surfaces based on these [Yang & Lee, 1999]. These methods are facing limitations in creating a topologically consistent edge structure. *Region based* methods start by grouping points that probably correspond to the same surface into regions and later deriving the edge structure from that.

*Region growing* methods fit surfaces and refine regions iteratively [Vieira & Shimada, 2005]. The main difficulties faced by these approaches is the question of determining the seed points for starting the regions.

The classical image segmentation algorithm of watersheds has been adopted to triangular surfaces [Mangan & Whitaker, 1999] and is popular for its simplicity and efficiency. It gives reasonable partitioning on organic objects, but is unsuitable for capturing the details of a complex mechanical engineering part. Hierarchical discrete Morse segmentation is a similar algorithm with stronger theoretical background [Edelsbrunner et al., 2002].

Beside the general purpose segmentation algorithms, several solution have been reported that deal with a limited subset of surface types or working on specific classes of objects.
2.3 Curves on polygonal meshes

Polylines running on the polygonal mesh can be generated in different ways. *Graph-based* methods try to find the extrema of some global function, e.g., shortest path between two points [Kanai & Suzuki, 2000]. The *parametric* approaches assign a two-dimensional parametrization to some part of the surface and map curves defined in the parametric domain onto the surface [Kass et al., 1988]. *Local estimation* methods compute geometric quantities based on local neighborhoods and generate polylines by tracing [Lavoué et al., 2005].

Spatial B-spline representation is more convenient for editing and fairing curves. Fairing methods can be classified into two main groups: those that affect the curve around some location only (*local*) [Farin & Sapidis, 1989], and those that modify the full curve (*global*) [Poliakoff, 1996]. These methods work by decreasing some kind of (linear) stress/energy function by moving the control points. Recent publications suggest starting by the beautification of the *curvature fence*, which is then followed by the construction the curve that implies that fence [Wang et al., 2004].

2.4 Generating consistent segmenting curve networks

Methods that generate consistent segmenting curve networks typically require additional user interaction. There have been reported methods that build consistent structures [Várady & Benkő, 2000, Kós et al., 1999], but these are research prototypes that work on a limited set of surface types. Vertex blends are generated by the underlying external CAD system rather than reconstructed from the measured data.

Vertex blending is itself a complicated problem in constructive CAD. The blending process can be categorized into three classes based on its complexity [Várady & Hoffmann, 1998]. The construction of the vertex blend faces difficulties even in the simplest case, e.g., determining the termination of connecting features, ordering, etc. The referred work analyzes these problems in details and suggests a set simple and intuitive rules, which use so-called *setback vertex blends* for uniform handling of different cases [Várady & Rockwood, 1997, Braid, 1997].
3 Aims and objectives

According to our best knowledge, no digital shape reconstruction methods have been published on automatic segmentation and generation of a CAD-conform model from measured data. Some of the well-known algorithms are only applicable to models with restricted classes of surfaces, while others are limited to accurate, noiseless input and do not work well on real measured data. The bottleneck of digital shape reconstruction in practice is the amount of manual work needed for drawing the exact region boundaries; this is almost impossible for complex engineering parts due to the large number of bounding faces.

We aim to develop a new faithful segmentation method which is capable of performing the segmentation automatically, or with minimal user interaction, that is, our main goal is to:

- separate primary regions and highly curved regions of connections and vertex blends;
- create complete and consistent segmenting curve network without topological limitations, which is isomorphic to the boundary representation of the final CAD model;
- provide an automatic procedure with no or minimal user assistance;
- develop a computationally efficient and robust procedure, that can be used for large scanned data sets and objects with high complexity.

As part of this:

1. we were aiming for a segmentation method that is suitable for an advanced reverse engineering system, that is, supports different surface types used by engineering parts and is capable of generating a complete and consistent CAD model;

2. set the goal to develop a hybrid method relying on mesh polylines and spatial B-spline curves, since the feature boundaries can be well approximated by local estimations, while parametric B-spline curves are essential for creating fair, compact and editable models;

3. in order to construct a consistent segmenting curve network of the independently generated boundary, we develop methods that determine the extent and the boundaries of vertex blends, and to resolve the intersecting/overlapping features.
4 Methodology of the research

The key topic of this dissertation is computer-aided geometric design, including the geometry of discrete surfaces and differential geometry of continuous curves. To understand the problems and to achieve new theoretical and practical results, basic knowledge in mechanical engineering was also essential.

At the beginning of this research, I’ve studied the literature on digital shape reconstruction (formerly reverse engineering). Parallel to this, as a developer at the Hungarian office of the U.S. based Geomagic corporation, I learned the state-of-the-art reverse engineering technologies.

Based on these I was able to analyze the basic problems with the solutions available around 2005. I have identified that segmentation is a critical step of digital shape reconstruction from both quality and automatization viewpoint, without any satisfactory solution available.

After I worked out the basic mathematical algorithms, I have implemented a prototype. I had the opportunity to test the theoretical results on measured data sampled from real, industrial parts. Based on the observations and analysis of the results, I have improved the original algorithms (handling of special cases, optimization of parameters, computational efficiency).

Parallel with the previous steps, I have published my results on different domestic and international conferences and journals. Along with the related results of my co-workers, we have filed a patent application. Majority of the algorithms presented in this dissertation have later been implemented in Geomagic Studio.
5 Results

Thesis 1. Detecting primary regions on triangular meshes.

1.1 I have defined the \textit{sharp edge filter}, which aims to separate sharp edges from blends with small radii on triangulated surfaces (Section 2.2.1).

1.2 I have introduced a new method for optimizing the size of the \textit{local neighborhood} that is used for filters (Section 2.2.2), which significantly improves the accuracy of estimations and the quality of the segmentation.

1.3 I have developed a new, \textit{neural networks} based segmentation algorithm that determines certain characteristic parts of an object based on a few examples (Section 2.2.3).

1.4 I have extended a well-known, Morse theory based hierarchical mesh partitioning algorithm with a new, volume based criterion that significantly improves the segmentation of primary regions on mechanical engineering objects (Section 2.3.1).

1.5 I have developed an algorithm to detect the \textit{separator sets} lying between the primary regions, which correspond to the connecting surfaces and vertex blends of the to-be-created CAD model (Section 2.3.2).

1.6 I have developed a new algorithm that generates the \textit{feature skeleton} based on the separator sets, which is describes the simplified topological structure of the object and determines the bounding topology of the final CAD model (Section 2.3.3).

Thesis 1 is based on publications [4, 2, 1] and Chapter 2 of the dissertation.

Thesis 2. Generating and modifying curves on meshes.

2.1 I have defined a new, \textit{general method for tracing polylines on meshes} (Section 3.2.1), which is capable of solving different tracing problems (e.g. tracing vector fields, smoothing, blending, etc.).

2.2 Based on the general tracing technique, I have developed algorithms for generating characteristic lines of features (midlines, cross-sectional and longitudinal boundaries) (Section 3.2.2).

2.3 I have improved a \textit{B-spline smoothing} algorithm to get optimized results on fairing characteristic feature lines (midlines, cross-sectional and longitudinal boundaries) to get uniform curvature distribution and exclude unnecessary inflections (Section 3.3.1).
2.4 I have developed heuristic methods to optimize the movements of interpolating points in a curve networks, in order to minimize the shape distortion of adjacent curves (Section 3.3.2).

2.5 I have developed new algorithms for conversion between two possible curve representations, that is, the approximation of polylines on the mesh with interpolated B-spline curves, and the projection of interpolated B-splines onto the triangulated surface (Section 3.4).

Thesis 2 is based on publications [3, 6, 7, 1] and Chapter 3 of the dissertation.

**Thesis 3** Generating consistent segmenting curve networks.

3.1 I have developed an algorithm to determine the center of vertex blends (Section 4.2), which handles all configurations of blending convex/concave features.

3.2 I have developed a new method to compute the optimal setback distances at vertex blends (Section 4.3.1).

3.3 I have analyzed the possible geometric configurations of the boundary curves at vertex blends, and I have developed a new algorithm to construct the spring curves (Section 4.3.2).

3.4 I have developed a procedure to ensure the consistency of segmenting curve networks by detecting overlapping features and interfering vertex blends, repositioning their boundary curves and resolving self-intersections of the network (Section 4.4).

Thesis 3 is based on publications [5, 7, 1] and Chapter 4 of the dissertation.

The article that appeared in the journal Computer-Aided Design [7] has been cited by 11 independent publications till the end of 2009.
6 Grants and applications

6.1 Research grants

This research has been supported by Geomagic Hungary Ltd. and Geomagic Inc. The results are part of a patent application [1] and have been partially contributed to the completion of the following grant:

- Advanced Reverse Engineering Techniques, ADREN)  
  (Korszerű módszerek a mérnöki visszafejtésben)  
  Hungarian Ministry of Culture and Education, OMFB-01979/2002

In the recent years the international research and development team at Geomagic was awarded two grants by the National Science Foundation of the United States. The results of my dissertation have contributed to the success of the following Small Business Innovation Research grants:

- Creating functionally decomposed surface models from measured data  
  (SBIR #0450230)

- Applications of Morse theory in reverse engineering (SBIR #0521838)

6.2 Software application

Geomagic has been developing products and solutions for capturing and modeling three-dimensional physical objects (http://www.geomagic.com). Geomagic Studio is a market-leading state-of-the-art digital shape reconstruction system, that supports the whole process of reconstruction (triangulation, segmentation, surface fitting, etc.).

The results of research related to my dissertation have been utilized by the segmentation module of Geomagic Studio version 10. The previous versions of the software used to create surface models of tiled quadrilateral patches. The new module enables to detect the structural design of the object more-or-less automatically, thus to create a high quality CAD model according to the design intent. A regular boundary-representation is generated, where the faces are trimmed by edge loops from larger surface entities.

The reconstruction of a real industrial part is depicted in Figure 4. Figure (a) shows the input triangulation, and (b) shows the CAD model that was generated automatically.

The steps of the process are depicted in 5. Figure (a) shows the mean curvature estimated on the triangulation, (b) shows the segmenting curve network and (c) shows the automatically generated CAD model.
Figure 4: Molding

(a) Mesh

(b) Automatically reconstructed CAD model
Figure 5: The steps of the reconstruction process

(a) Estimated curvature and feature skeleton on the mesh

(b) Segmented curve network on the mesh

(c) Automatically generated CAD model
Bibliography


Related publications of the author


Independent citations of the authors’ publications


