4 REPRESENTATION AND PROCESSING OF SURFACE DATA

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INTRODUCTION

In recent years optical 3D sensors have become powerful tools for *reverse engineering*. The shape of a three-dimensional object is sampled for that purpose and turned into a description for computer aided design (CAD). The method enables processing of physical design models on a computer (see Section 8.1). Using computer aided manufacturing (CAM) techniques like numerical controlled (NC) milling or stereolithography, three-dimensional replicas of the digitized objects can be made. In dentistry such methods are used to scan teeth or plaster casts and to automatically produce crowns and inlays from the data.

The raw data delivered by the 3D sensors (*range images*) are not well suited for direct use in CAD systems, as the data are given in the local coordinate system of the sensor. Moreover, the range images do not really describe surfaces, but clouds of point coordinates in 3D space. The amount of data points may be very large (from millions to hundreds of millions). Furthermore, data points are usually distorted by measuring errors like noise, aliasing, outliers, etc. Thus, several problems have to be addressed before a complete surface description can be achieved:

1. The *preparation of the raw data* refers to noise removal, data reduction with small loss of information, detection of outliers, compression or any combination of it. We present problems and solution techniques in Sections 4.1 and 4.3.
2. Detection of features. These can be used for classification purposes or for analysis and interpretation. In addition, features are often used for registration or matching

(see Section 4.2). Here the task is to combine several data sets into best possible alignment. This is necessary, e.g. when an object is scanned from different view points, which often cannot be avoided due to the special geometry of the object.

3. The transformation of the single range images into a common global coordinate system (*registration*, see Section 4.2).
4. Fusion of different views obtain global, topologically correct and geometrically exact representation of the complete model (see Section 4.4).
5. The construction of an analytic surface description (see Section 4.6) in order to further process it in CAD/CAM application, or to do a comprehensive surface analysis (surface interrogation). An example of the latter will be given in Section 8.2.

In practice these items will not be treated separately or necessarily in the specified order. At present, the most frequently used method for the final surface description is a polynomial *tensor product (TP)* approximation to the data points (Bézier or B-spline). This is the de facto standard in automotive industry, aircraft design and many other CAD/CAM-based industries. Up to now these methods require much interactive control. A simpler and more direct way is to generate a polygon mesh, which is sufficient for some applications, and sometimes even desired, e.g. for visualization purposes or computer graphics oriented applications. Tensor product surfaces are necessary for *reverse engineering*, where designers want to modify, or evaluate free form surfaces reconstructed from digitizing real objects.

4.1 POLYGON MESHES

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Triangle meshes are the simplest type of polygon meshes. Since polygon meshes can be converted into triangle meshes simply by triangulating all n-gons with $n > 3$, this introduction focuses on triangle meshes.

4.1.1 Advantages of Triangle Meshes

At present triangles are the only surface primitive that can be rendered directly by graphics hardware. Hence, all surface descriptions must be approximated by triangle meshes for interactive visualization. Triangle meshes are very flexible. In contrast to tensor product surfaces, for example, they can describe surfaces of arbitrary topology, even with non-manifold elements. Furthermore, the density of vertices can be locally adapted to the surface curvature. Since triangles are a very simple kind of geometric primitive, algorithms for triangle meshes are usually efficient and robust.

4.1.2 Topology and Geometry

The neighborhood structure of a triangle mesh (the triangles and edges) is called the *topology* of the mesh, while the coordinates of the vertices describe its *geometry*. The basics on topology, geometry and graph theory can be found in textbooks on computer graphics [741, 227, 207, 622].

A triangle mesh consists of *vertices* (*knots*, *points*), *edges* and *triangles*. Important topological features are *holes*, *genus* and number of *connected components.* An edge that is bounded by a single triangle is called a *boundary edge*. A closed polygon of boundary edges encloses a *hole,* which usually is an artifact. Physical objects never have such kind of holes, as there must always be an outside and an inside. Physical holes have the shape of 'donuts'. The *genus* of an object is the number of its 'donuts'. A sphere has genus 0, a torus genus 1, etc. The relation between these features is given by the *Euler-Poincaré Equation*

$$V - E + F - H = 2(C - G), \tag{4.1}$$

where V is the number of vertices, E the number of edges, F the number of facets (triangles), H the number of holes, C the number of components, and G the sum of the geni of all components. For meshes with very many triangles ($V, E, F \to \infty$) or for objects which are homomorphic to a sphere ($H = 0, G = 0, C = 1$) this simplifies to the *Euler Equation*

$$V - E + F = 2. \tag{4.2}$$

The fact that every triangle is bound by three edges leads to

$$2E = 3F. \tag{4.3}$$

Inserting this into Equation 4.2 results in

$$F \approx 2V \tag{4.4}$$

and

$$E \approx 3V. \tag{4.5}$$

Thus, a large mesh consists of approximately twice as much triangles and three times as much edges as vertices.

4.1.3 Mesh Representations

A two-dimensional image is usually stored as a 2D array of pixels. The implicit order of that structure enables fast and simple access to adjacent pixels. In general it is not possible to describe triangle meshes, other than those generated from single range images, with such a simple structure.

Explicit Mesh Structure. The simplest structure to describe a mesh with m triangles is a list of $9m$ float values. Each triangle is represented by 3 coordinate triples $(x, y, z)_i$, $0 \leq i < 3$, that define the positions of the vertices. A mesh with n vertices needs approximately $18n$ float numbers. Since a vertex is usually shared by several triangles (6 on average), each vertex is stored several times. Thus, this structure is very inefficient. Beyond that, the topology is not represented explicitly. Shared vertices must be identified by identical coordinates, which is expensive (float compare) and sometimes difficult, as the geometrical positions may vary due to numerical limitations.

Indexed Mesh Structure (Shared Vertex). The above mentioned disadvantages can be avoided by storing two separate lists for geometry and topology. The geometry is stored in an array of n coordinate triples $(x, y, z)_i$, $0 \leq i < n$, for the n vertices (*vertex list*), the topology in an array of m integer indices, $(a, b, c)_j$, $0 \leq j < m$, that address the positions of the three triangle vertices in the coordinate list (*index list*). Since the geometry is stored without any redundancy, this structure needs only $3n + 3m \approx 9n$ numbers ($3n$ floats and $6n$ integers). Although vicinity data are not stored explicitly, adjacent triangles can easily be detected in linear time by identical indices. Since many algorithms repeatedly request this information, usually more elaborate structures that enable extraction of vicinity information in constant time are used [374].

Hierarchical Ring Structure. This data structure [624] enables direct access to the neighbors of each vertex and to the triangles that share a certain vertex. Like in the indexed mesh structure, the triangles are defined by an array of index triples. The vertex list contains the coordinates of each vertex, a list of pointers to all triangles that share that vertex and a list of its direct neighbors. Since the number of joining triangles and adjacent vertices is not constant and bound, these structures are realized by chained lists. Inserting and deleting triangles thus are rather complex operations and may result in fragmented memory. Memory demands depend on the number of neighbors of each vertex. With an average of 6 neighbors, $(3 + 6 + 6)n + 3m \approx (15 + 6)n \approx 21n$ integer and float numbers are required for a mesh with n vertices and m triangles (plus additional overhead for the chained lists).

Winged-Edge Mesh Structure. The most popular mesh structure is the winged-edge representation for arbitrary polygon meshes [46]. The focus of this data structure is the edge. Each edge e contains pointers to its endpoints v_0 and v_1, the two adjacent faces f_0 and f_1 and to the 4 edges e_{0-}, e_{0+}, e_{1-} and e_{1+} (the 'wings' of e) that bound f_0 or f_1 and end in v_0 or v_1, respectively (see Figure 4.1). For each vertex a pointer to an arbitrary one of its joining edges is added to the coordinates in the vertex list. Likewise each face points to an arbitrary one of its bounding edges. This structure enables direct access to all topology information that may be required. A triangle mesh with n vertices, m triangles and l edges needs $8l + m + 4n \approx (24 + 2 + 4)n \approx 30n$ numbers. For storing non-manifold structures, special considerations are required.

Directed Edge Mesh Structure. This is an *half-edge*[1] based data structure for exclusive description of triangle meshes [105, 104]. Each vertex contains a pointer to an half-edge that originates from it (see Figure 4.1). Triangles are not represented explicitly. The half-edges are sequentially stored in an array, in such a manner that the half-edges $3i$, $3i + 1$ and $3i + 2$ define the i-th triangle. Each half-edge contains a pointer to its predecessor e_{prev}, its neighbor e_{neig} and its endpoint v_1. A mesh with n vertices and m triangles needs $(3 \cdot 3)m + 4n \approx 18n + 4n = 22n$ numbers. It is possible to omit e_{prev}, as it can be extracted from the edge array, resulting in a slower

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[1] A half-edge is an oriented edge. Each ordinary edge consists of two half-edges with opposite orientation.

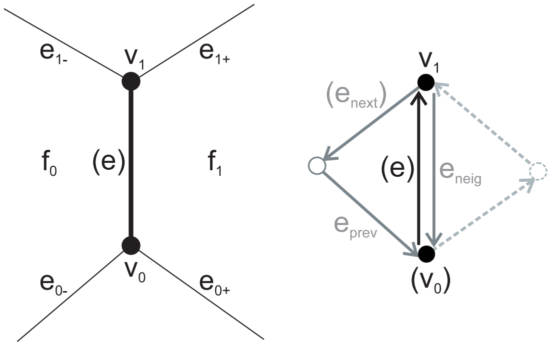

Figure 4.1. Associated pointers of edge e in the winged edge (left) and the directed edge (right) data structure.

performance. In this case only $(2\cdot 3)m+4n \approx 12n+4n = 16n$ numbers are required. By default this data structure fails in describing non-manifold objects, too.

Quad-Edge Mesh Structure. The quad-edge structure [268, 521] is extremely general, representing any subdivision of 2-manifolds, permitting distinction between the two sides of a surface, allowing the two endpoints of an edge to be the same vertex, permitting dangling edges, etc. Each edge record contains four circular lists: for the two endpoints, and the two adjacent faces. In contrast to the previous data structures, these pointers do not address positions in the vertex or face list, but the next edge record in the vicinity of the corresponding vertex or edge. Vertices and faces are represented by *rings* (cycles) in Figure 4.2. For example, face A is the ring of edges (a, e, f) and vertex 2 is the ring (a, b, e). The vertex and face lists contain pointers to an arbitrary edge on the corresponding ring, to give access to that ring. The dual of a given graph is simply found by interpreting the vertex rings as faces and vice versa (no computation is necessary). A triangle mesh with n vertices, m triangles and l edges needs $4l + m + 4n \approx (12 + 2 + 4)n \approx 18n$ numbers.

4.1.4 Meshes with Attributes

The previous data structures only consider the geometry of three-dimensional objects. Frequently, additional attributes like color, material, normals, texture coordinates, tension or pressure are required. They can be assigned to triangle meshes in different ways:

- to each vertex of the mesh,
- to each triangle (needs twice the space of the previous structure),
- to each vertex of each triangle (needs six times the space of the first structure).

The last structure requires the most memory but offers high flexibility, as it includes the others as well. On the other hand it is difficult to use this structure for vertex- or

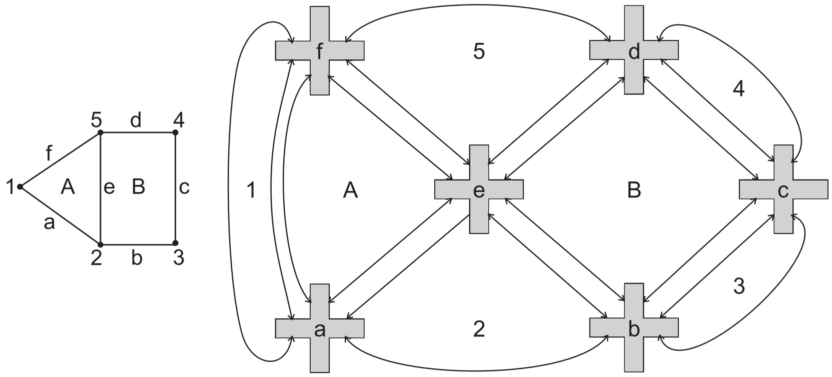

Figure 4.2. A simple plane graph with faces A and B, edges a–f and vertices 1–5 (left) and its quad-edge representation (right). Each edge record (gray crosses) consists of 4 pointers to the next edge that shares the same vertex (2 pointers) or bounds the same face (2 pointers). Thus, vertices and faces are represented by circular lists.

triangle-based standard algorithms which usually cannot handle multiple attributes per vertex or triangle.

4.1.5 Parametric Meshes

Some kinds of meshes can be represented in parametric form which allows to use algorithms that are simpler and more efficient than those for general meshes. Range images, for example, are sometimes named 2.5D surfaces, as each vertex is defined by its height above a parameter plane. Triangle meshes that were generated by tesselating a parametric surface are parametric as well. It is not necessary to store the triangles of parametric meshes explicitly, as they can be reconstructed by Delaunay-triangulating the vertices in parameter space [521]. It is sufficient to save the parameters of each vertex instead. Attributes must be assigned to the vertices then, not to the triangles.

4.1.6 Hierarchical Mesh Representations

Conventional file formats store the data serially. The first p percent of a file contain p percent pixels of an image in full resolution. A hierarchical data stream, in contrast, transmits the whole image at any time, starting with a low resolution. Details are added while the transmission proceeds, until the whole image information is transferred (see Figure 4.3). The regular structure of 2D images enables progressive encoding without any overhead. Simple methods for hierarchical representation of two-dimensional images are interlacing techniques and decomposition by Haar wavelets [674]. 3D models may be represented hierarchically as well (see Figure 4.4). The CPU only reads as many triangles as fit into memory or can be rendered in real-time. Because of the irregular structure of general triangle meshes, it is not possible to find hierarchical representations in a straightforward manner.

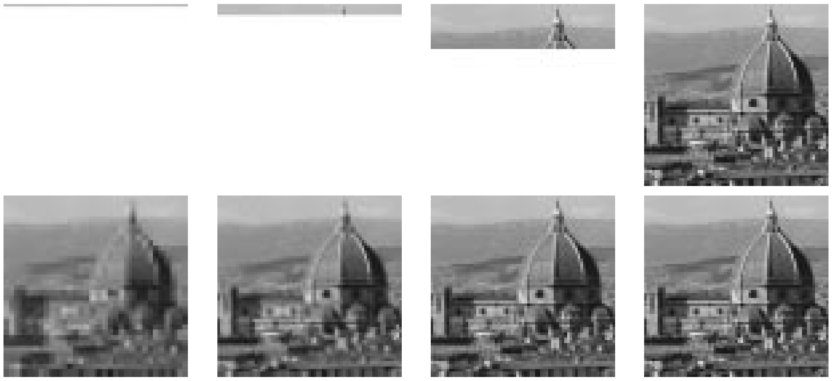

Figure 4.3. Sequential and hierarchical representation of an image. Images of the same column need the same storage space.

Discrete Levels of Detail. The most popular method for the hierarchical representation of triangle meshes is to store discrete *levels of detail (LOD)* in a sequence of independent meshes with increasing resolution. Each new level contains the whole image information of its predecessor, resulting in a large data overhead. For that reason only a few levels are usually used and switching between different levels is clearly visible (*popping*). Mesh reduction techniques are usually required to generate different resolution levels (see Section 4.1.7).

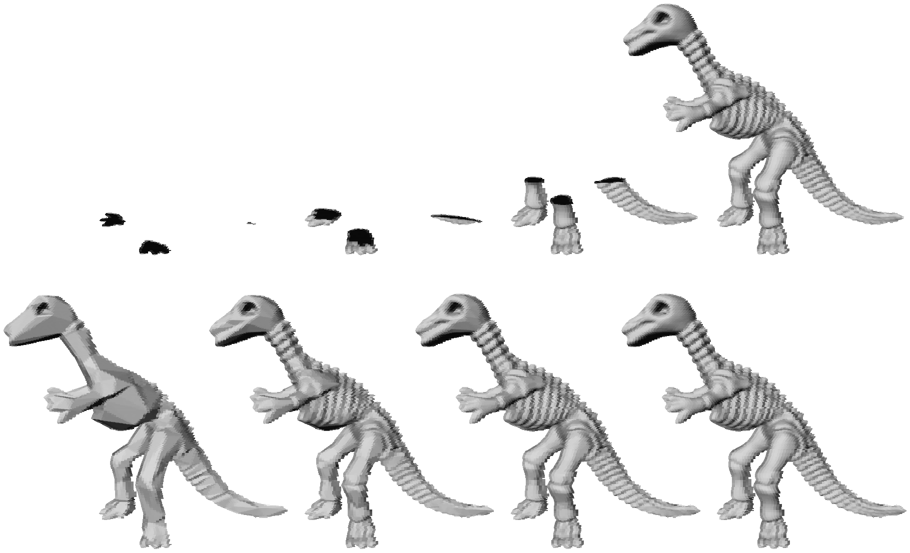

Figure 4.4. Sequential and hierarchical representation of a 3D model. Models of the same column need the same storage space.

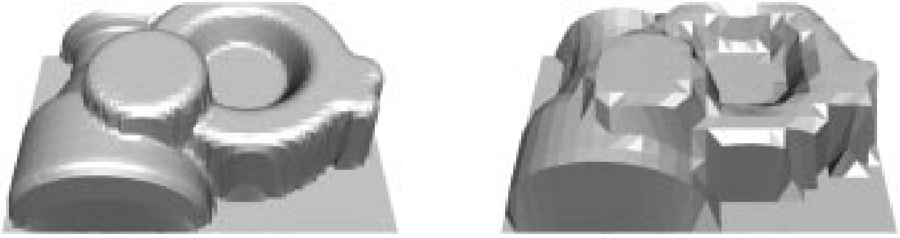

Figure 4.5. Approximation (right) by subsampling a dense regular mesh (left).

Subsampling. Regular triangle meshes like single range images may be stored by interlacing techniques. Similar to two-dimensional images a coarse approximation of a mesh that is defined on a rectangular grid can be found by subsampling every i-th column and every j-th row of the data array. A hierarchy is constructed by reducing i and j iteratively jumping over cells which are already stored in preceding levels (see Figure 4.5). This method solely depends on the topological structure of the data. The geometry is not considered. As a result, details with high frequency are lost in low resolution levels.

Wavelet Decomposition. For regular structures (e.g. images) *multiresolution analysis* based on *wavelets* is possible [674]. The data are decomposed by a series of high and low pass filters. In contrast to the sine and cosine functions of Fourier analysis the wavelet basis functions are spatially and temporally limited. Thus finite signals are easier to process while avoiding any artifacts. The simplest type of wavelets for images

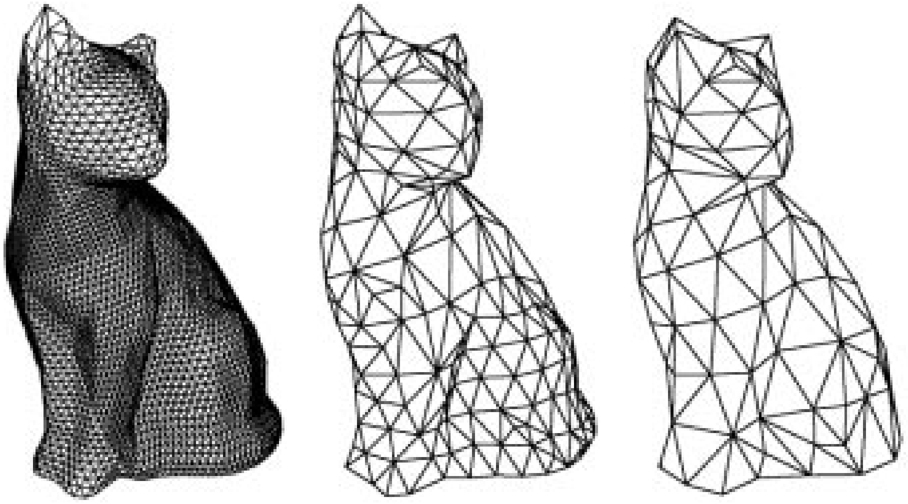

Figure 4.6. A mesh with subdivision connectivity (left) and different decomposition levels using wavelets (middle and right).

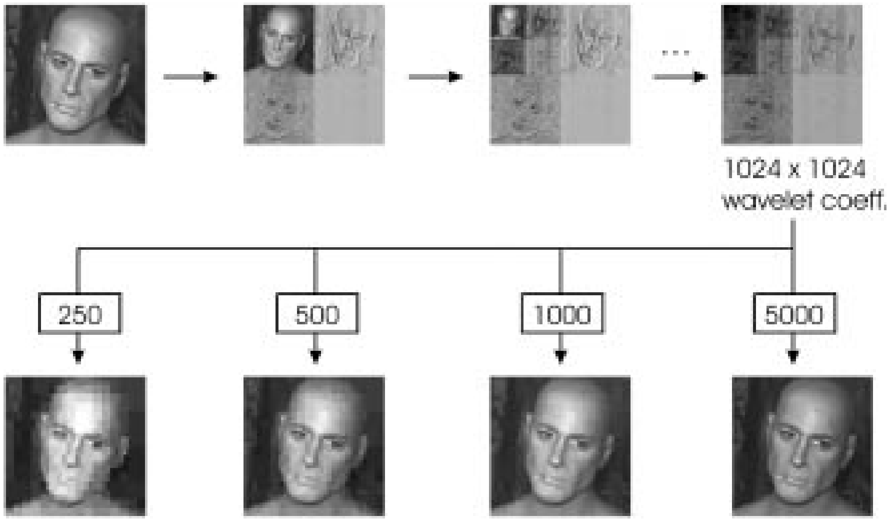

Figure 4.7. Image compression by wavelets (upper: different decomposition levels of a 1024×1024 image resulting in 1024^2 wavelet coefficients, lower: reconstruction solely using the 250, 500, 1000, resp. 5000 most significant coefficients).

are *Haar functions* which simply add (low pass) or subtract (high pass) neighboring pixels. Lounsbery et al. [197, 454] have generalized this approach for meshes with *subdivision connectivity*: all vertices (with singular exceptions) must have the same number of neighbors (see Figure 4.6). The original mesh is approximated by a coarse one that is adequate just to describe the topology of the object. Usually a few hundred triangles are sufficient. Objects which are homomorphic to a sphere may even be approximated by a tetrahedron. A series of correction terms (*wavelet coefficients*) is computed. These are necessary to refine the basic mesh by recursive subdivision until the original mesh is reconstructed. Each subdivision level owns a complete record of wavelet coefficients. It is possible to interpolate continuously between sequent levels. Structure dependent mesh reduction is simply done by eliminating small coefficients (see Figure 4.7). General meshes must be *remeshed* in order to achieve subdivision connectivity [197, 422]. In this case the original mesh can only be reconstructed approximately.

Progressive Meshes. In order to get a coarse approximation of a general dense mesh, details can be eliminated by successively removing vertices, edges or triangles (see Section 4.1.7). It is possible to invert this process by recording all executed operations (see Figure 4.8). Each step of this reconstruction process represents a complete approximation of the original mesh. The most popular implementations of this type of multiresolution hierarchy are *progressive meshes* [324] and its generalization to arbitrary dimensions, the *progressive simplicial complexes* [552]. These representations generate no data overhead and enable exact reconstruction of the original mesh, hierarchies with fine graded levels and sequential access to different levels.

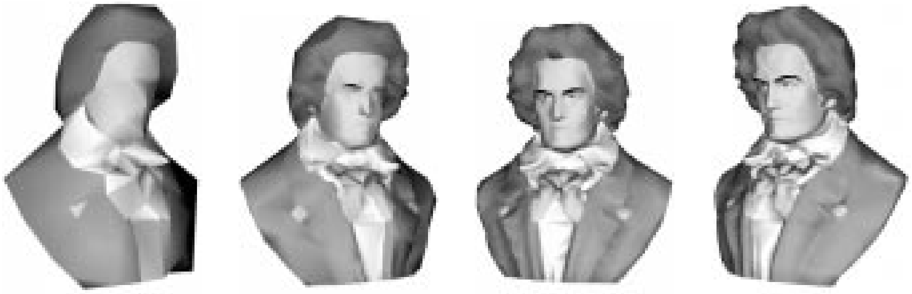

Figure 4.8. A coarse mesh with 256 triangles (left) is successively refined by adding vertices and triangles until the original mesh with 5030 triangles is reconstructed exactly (right).

4.1.7 Mesh Reduction

Mesh reduction techniques are used to reduce the number of triangles of a dense triangle mesh. In recent years researchers have proposed a variety of methods. Surveys are published by Schroeder [620] and Cignoni et al. [130]. Mainly three approaches are used: multiresolution analysis by wavelets, retiling (remeshing, clustering) and iterative algorithms.

Retiling, *remeshing* and *clustering* methods generate completely new meshes by sampling new vertices. Different resolution levels are independent from each other, so that only discrete levels of detail (LOD) can be created. Turk [715] randomly places new vertices with curvature dependent density into the original mesh and thereafter removes the original ones (*retiling*). Rossignac and Borrel [581] use a coarse three-dimensional grid to merge all vertices within one voxel (*vertex clustering*).

Most frequently *iterative* approaches are used [624, 327, 111, 389, 324, 579, 237, 374, 621, 622, 104]. Topological and geometrical operations are used to remove vertices, edges or triangles from the dense mesh. This process is iterated until a given approximation error is reached or until no further thinning is possible. Alternative algorithms start with a coarse approximation that is refined iteratively by inserting new elements [218, 726]. Both methods enable the creation of progressive LODs.

Geometrical and Topological Operations. Triangle meshes can be modified using geometrical and topological operations. *Geometrical operators* change the geometrical positions of the vertices and leave the topology (connectivity) unchanged, while *topological operators* modify solely the connectivity of the mesh. The following sections introduce the ones most frequently used.

Vertex Change. The geometrical operator *vertex change* modifies the position of a vertex (see Figure 4.9). It may be used for filtering (see Section 4.3.2) or may be a component of more complex operators. Triangles which are influenced by this operator are marked gray in Figure 4.9.

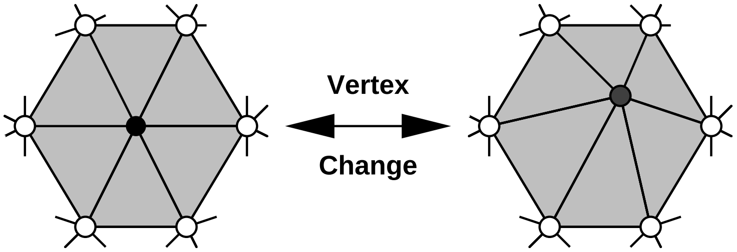

Figure 4.9. The vertex change operator moves the geometrical position of a vertex.

Vertex Removal and Vertex Insertion. The topological operator *vertex removal* eliminates a vertex and re-triangulates the modified region (see Figure 4.10). Its inverse, the *vertex insertion* operator, is not purely topological, as it modifies geometry as well. Vertex removal may be used for iterative mesh reduction, vertex insertion for merging overlapping meshes (e.g. for mesh reconstruction, see Section 4.4, or for refining a coarse mesh by subdivision, see Section 4.3.3).

Edge Collapse and Vertex Split. The *edge collapse* operator removes a vertex by collapsing an edge (see Figure 4.11). Its inverse is called *vertex split*. In general the remaining vertex gets a new position. Hence, the edge collapse operator modifies geometry and topology as well. It is purely topological if one of the end points remains unchanged (sometimes it is named *half-edge collapse* then). In Figure 4.11 *supporting* (influenced) triangles are marked in light gray, triangles which are removed are marked in dark gray. Edge collapse and vertex split are often used for progressive meshes (see Section 4.1.6).

Algorithms for Mesh Reduction. Iterative mesh reduction is usually carried out by repeatedly using edge collapse or vertex removal operations. The quality of the resulting mesh is mainly determined by a proper choice of the candidates to be removed and by the order in which they are eliminated. Simple algorithms choose a certain element (edge or vertex) from the input list (random or sequential), remove it if possible (e.g. if a cost function does not exceed a certain threshold) and proceed to the next

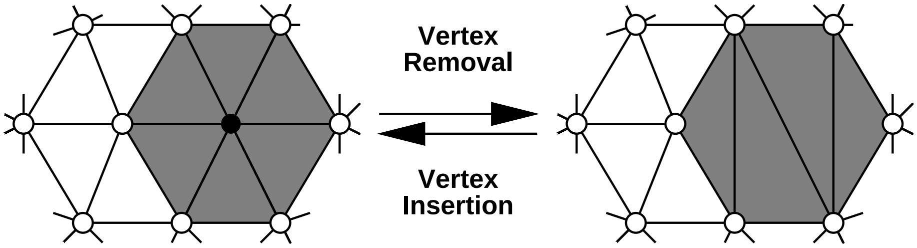

Figure 4.10. Vertex removal and its inverse vertex insertion remove or add two triangles.

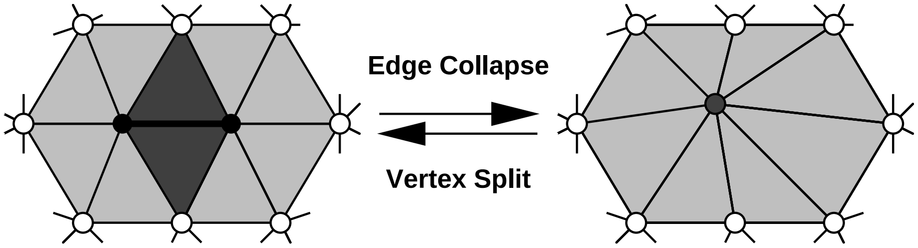

Figure 4.11. Edge collapse and its inverse vertex split remove or add two triangles (dark gray).

element [624, 327, 605, 384, 374, 622]. Best results are achieved if the candidates are sorted according to their costs [395]. The candidate with minimum cost is removed from the mesh and the candidate list is updated. This process is iterated until no candidate with a cost beyond the given threshold is left.

Cost Functions. Error bound mesh reduction techniques compute a cost function for the elimination of each single element (vertex or edge). This function may simply be the maximum distance (*global error*) between elements of the new mesh and the original one [389]. Since it is computationally expensive and impractical to compare the thinned mesh with the original one after each iteration, *local* methods estimate the global error [134, 579, 237, 374] (e.g. see Section 4.3.4) or simply evaluate the difference between two iterations [624, 605, 384, 621].

Merely using distance measures may result in surfaces with small approximation error but poor quality (see Figure 4.12). Hence, some authors use additional quality measures that evaluate the curvature characteristics of the resulting mesh [374, 104] or minimize the energy of a spring model [327].

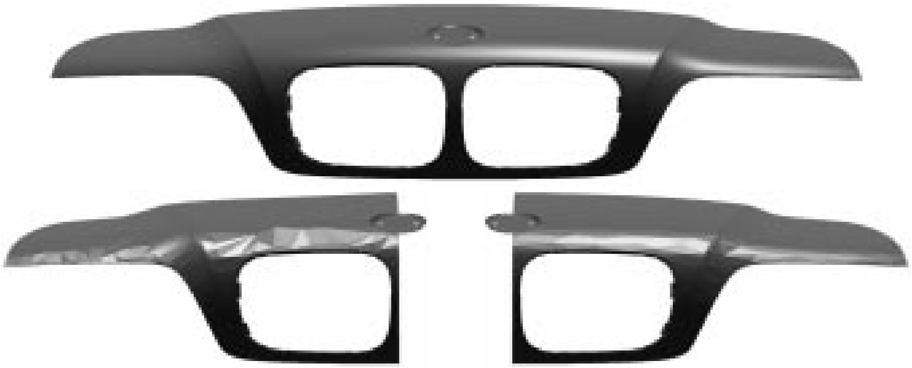

Figure 4.12. A dense mesh (top) is reduced with two different cost functions (bottom left: distance measure only; bottom right: distance measure and curvature dependent cost function).

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