

Watermarking Three-Dimensional Polygonal Models Through Geometric and Topological Modifications

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Abstract

This paper discusses techniques for embedding data into three-dimensional (3D) polygonal models of geometry. Given objects consisting of points, lines, (connected) polygons, or curved surfaces, the algorithms described in this paper produce polygonal models with data embedded into either their vertex coordinates, their vertex topology (connectivity), or both. Such data embedding can be used, for example, for copyright notification, copyright protection, theft deterrence, and inventory of 3D polygonal models.

A description of the background and requirements is followed by a discussion of where, and by what fundamental methods, data can be embedded into 3D polygonal models. The paper then presents several data-embedding algorithms, with examples, based on these fundamental methods. By means of these algorithms and examples, we show that the embedding of data into 3D polygonal models is a practicable technique.

Keywords: Geometric modeling, three-dimensional computer graphics, copyright protection, data embedding, steganography, data hiding, digital watermarking, digital fingerprinting.

1. Introduction

The proliferation of digital media such as the Internet and CD-ROMs has made it is to duplicate, distribute, and modify various kinds of digital contents, including images, texts, movies, audio data, and recently three-dimensional (3D) models. At the same time, this ease of manipulation has also prompted unauthorized duplication and distribution of valuable contents.

One way of addressing this problem is to add *watermarks* to the objects in which contents are stored. Watermarks are structures containing information that are embedded in a data object (e.g., an image) in such a way that they do not interfere with its intended use (e.g., viewing). They can be used, for example, to deter theft, to notify users of how to contact the copyright owner for payment of licensing fees, to discourage unauthorized copying, or to take inventory. The technology associated with watermarks in this sense is called *steganography*, *data hiding*, *(digital) watermarking*, *data embedding*, or *fingerprinting*.

This paper presents fundamental techniques and algorithms for embedding data into 3D models of geometry. Realistic applications of data embedding would require more sophisticated features, such as the provision of security through the use of encryption. However, a set of basic data embedding techniques presented in this paper serve as a foundation for methods adapted to the needs of more realistic applications.

Figure 1 shows an example of embedding data into polygonal models of dinosaurs using an algorithm described in Section 3.2. Each dinosaur model is marked with a distinct message. The message embedded in the triceratops model, “Copyright (C) DINOSAURS INC. <CR> Model #triceratops003 <CR> Contact <http://www.dinosaurs.org/>.”, can be extracted and displayed by clicking on the model while using a 3D model browser enhanced with the extracting capability. Such messages can be used, for example, to automatically connect the browser to a license server on the Internet to collect license fees.

In this paper, the addition of a watermark is called *embedding (or watermarking)*, and the retrieval of the information encoded in the watermark for perusal is called *extraction*, as illustrated in Figure 2. The object in which the information is embedded is called *cover-<datatype>*, the object with the watermark is called *stego-<datatype>*, and the information embedded is called *embedded-<datatype>*, following recommendations in [Pfitzmann96]. The suffix “<datatype>” varies according to the types of data such as image, text, or 3D model. For example, a text is embedded in a cover-3D-model to produce a stego-3D-model with embedded text.

The remaining part of this paper is organized as follows. The rest of Section 1 presents a brief review of related work. Section 2 first discusses requirements, followed by fundamental methods for embedding data in 3D models. These fundamental methods are combined to create several embedding algorithms, described in Section 3. We conclude with a summary and some remarks on possible directions for future work.

1.1. Related work

Data embedding has previously been studied for still images, movie images, audio data, and texts [Tanaka90, Walton95, Cox95, Braudway96, O’Ruanaidh96, Smith96, Zhao96, Hartung97]. In the case of 3D geometric models, the comment and annotation capabilities of scene description formats, such as the Virtual Reality Modeling Language (VRML) [ISO96], have been the primary means of adding information. However, these comments and annotations can be easily removed, either intentionally or unintentionally. For example, programs for converting from one 3D model format to another often remove comments and annotations. Consequently, comments and annotations cannot meet most of the requirements of watermarks.

2. Fundamentals of watermarking 3D models

2.1. Embedding requirements

While each application of data embedding into 3D models has its own set of requirements, the following three requirements are common to a majority of application scenarios.

Unobtrusive: The embedding must not interfere with the intended use of a model, such as viewing. One published example of image watermarking [Braudway96] used the visibility of the watermarks to good advantage, but in most applications, the watermarks must be unnoticeable in terms of the model’s intended use.

Robust: Robustness is crucial to the success of data embedding. Making the watermark indestructible is not a trivial problem. Note that this is different from making a message in the watermark unreadable.

With complete knowledge of how watermarks are embedded, any watermarks can theoretically be removed. With partial knowledge (e.g., the knowledge of the basic algorithm), the removal must be difficult enough so that it either interferes with the intended use of the models, or the cost of removal is greater than the value of the model.

Assuming the kind of use a VRML model has to expect, watermarks in a 3D model have to expect the following kinds of alterations during day-to-day use. Data format conversion often scrambles the orders of points, polygons and other geometrical primitives, and introduces floating-point-number representation errors. Models are geometrically transformed to construct a scene. While the geometrical transformations are often limited to rotation, uniform scaling, and translation, more general transformations, such as affine transformations are also common. Local deformations are occasionally

applied to reshape a part of a model. Topological alterations, such as resection of a desired part of a model and polygon simplification, may also be performed.

Watermarks in a model may also be attacked with the intention of destroying or altering them. Possible means of intentional attack include addition of random (or systematic) values to vertex coordinates and polygonal simplification.

If the degree of modification is limited so that the utility of the model is not compromised, watermarks in 3D models should *ideally* withstand all of these and other possible alterations, regardless of whether they are intentional.

Space efficient: A data-embedding method should be able to embed a non-trivial amount of information into models.

In general, above three requirements are at odds. For example, if one needs more robust embedding, the amount of data that can be embedded is reduced. The best trade-off depends on the application.

2.2. Embedding targets

A 3D model may contain a wide range of data objects. For example, a VRML 2.0 file includes geometry of objects defined by polygons, lines, or predefined shapes (e.g., cylinders, spheres, or cones). These objects have attributes, such as shininess, per-surface or per-vertex colors, per-surface or per-vertex normal vectors, per-vertex texture coordinates, and texture images. The file may also contain Universal Resource Locator links, pointers to sound data files, behavioral scripts written in a programming language. In the case of non-VRML models, the geometry of 3D objects may be represented by solids bounded by curved surfaces (e.g., Bezier patches), by voxel enumeration, and by many other means.

We argue that geometry is the best candidate for data embedding among the types of data object that could exist in 3D scene descriptions, since it is by definition the least likely to be removed.

Among the many possible representations of 3D geometry, we chose, for the study reported in this paper, *polygonal models* as the target (output) of embedding (see Figure 2). A “polygonal model” in this paper may include one or more of the following geometrical primitives: points, lines, polygons, connected polygons, polyhedrons, and connected polyhedrons. While some data-embedding algorithms require topology (connectivity) among points, topology can be added, for example, by Delaunay triangulation [O’Rourke94].

Inputs to the embedding algorithm may either be polygonal models or *curved surface* models. Embedding may be performed either during or after tessellation of the curved surfaces. For example, the

algorithm that will be described in Section 3.3 accepts curved surfaces as input and embeds patterns as it tessellates the surfaces. Embedding watermarks during tessellation can be advantageous in data embedding, because the embedding algorithm can exploit its large degree of freedom in choosing the number, position, and topology of vertices produced by the tessellation.

Other components of 3D scene descriptions can also be used for data embedding. Images for texture mapping and sounds are obvious targets of embedding. Per-vertex normal vectors, per-vertex texture coordinates, per-vertex colors, or even face colors can also become targets of data embedding. These non-geometrical components, however, are less crucial to 3D scenes and have higher chances of alteration or removal than geometry.

2.3. Embedding primitives

There are two attributes in a polygonal model of geometry that can be modified in order to add watermarks. One is the *geometry* of the geometrical primitives (e.g., points or triangles) and the other is the *topology* among these primitives. Units of alteration, either geometrical or topological, are called *embedding primitives* in this paper.

2.3.1. Geometrical embedding primitives

Geometrical values – specifically, the coordinates of points and vertices – can be modified to embed data. Notice, however, that information encoded directly in coordinate values is vulnerable to almost any kind of geometrical transformation. It is thus advantageous to employ geometrical embedding primitives that are *invariant* to certain classes of geometrical transformations. The following lists examples of embedding primitives derived from vertex coordinates that are invariant to increasingly larger classes of geometrical transformations.

1. Altered by all the transformations listed below
 - a. Coordinates of a point.
2. Invariant to translation and rotation
 - a. Length of a line.
 - b. Area of a polygon.
 - c. Volume of a polyhedron.
3. Invariant to rotation, uniform-scaling, and translation
 - a. Two quantities that define a set of similar triangles (e.g., two angles).
 - b. Ratio of the areas of two polygons.

4. Invariant to affine transformation
 - a. Ratio of the lengths of two segments of a straight line.
 - b. Ratio of the volumes of two polyhedrons.
5. Invariant to projection transformation.
 - a. Cross-ratio of four points on a straight line [Farin96].

Upon embedding, the quantity of the primitive is modified, typically by a very small amount, so that subsequent displacements of vertices do not affect the intended uses of the model.

2.3.2. Topological embedding primitives

Watermarks can be embedded by changing the topology of a model. The change may also involve change in geometry as a side effect (e.g., inserting or displacing vertices), but information is embedded mainly in the topology.

Simple examples of topological embedding primitives include encoding of a binary symbol by using two alternative ways of triangulating a quadrilateral, as shown in Figure 3a, or two different mesh sizes, as shown in Figure 3b.

2.4. Embedding primitive arrangements

For practical data embedding, multiple embedding primitives must be arranged so that a collection of embedding primitives functions as a watermark to store a substantial amount of information.

Data objects such as image and audio data already have regular implicit ordering of embedding primitives. For example, an image has a rectangular 2D array of pixels. In the case of 3D geometrical models, arrangement of the embedding primitives is somewhat more involved.

An example of arrangements of embedding primitives for 3D geometrical models is a 1D arrangement generated by sorting triangles according to their areas. Another example is a 2D arrangement of triangles based on the connectivity of triangles in an irregularly-tessellated triangular mesh.

Arrangements of embedding primitives can be established for 3D polygonal models by the following two methods.

a. Topological arrangement employs topological adjacency, such as adjacency of vertices, to arrange embedding primitives. Topological arrangement is applicable to both topological and geometrical embedding-primitives. It can survive a geometrical transformation, but is not resistant to topological modification.

b. Quantitative arrangement employs inequality relations among the quantities associated with embedding primitives, such as volumes of polyhedrons, to sort those primitives.

In both arrangement methods, it is often necessary to find an *initial condition* – for example, the first primitive of a one-dimensional arrangement – in order to initiate an arrangement. Obviously, both arrangement and initial condition must be robust with respect to expected disturbances, such as geometrical transformations, or the watermarks will be lost.

In this paper, arrangements of embedding primitives are classified by their locality into *global*, *local*, and *subscript arrangements*. Figure 4 shows examples of these three types of arrangements based on topological adjacency.

a. Global arrangement arranges a set of all the embedding primitives in an embedding target.

b. Local arrangement arranges each of multiple disjoint subsets of every embedding primitive in an embedding target.

c. Subscript arrangement is similar to local arrangement, but with a very small subset size (e.g., a few primitives). Such subset is called *Macro-Embedding-Primitive (MEP)*. Each MEP is associated with a special kind of data, namely, a unique subscript. Subscripts map a set of embedding primitives into a sequence.

A global arrangement tends to have higher information density than the other two methods. On the other hand, by repeatedly embedding a message, local and subscript arrangements can be made more robust with respect to partial disruption of arrangements due, for example, to resection of a model .

Arrangements of embedding primitives are used to embed data in two alternative ways, by means of what we call *symbol-sequence-embedding* and *pattern-embedding*.

a. The *symbol-sequence-embedding* method embeds an ordered sequence of symbols, such as a character string. Symbol-sequence-embedding typically employs a 1D arrangement of embedding primitives.

b. The *pattern-embedding* method embeds patterns that are visually recognizable if presented to human beings. For example, shapes of letters can be cut into a triangular mesh as a visible watermark that is visible if displayed by using a wire-frame rendering. Not all watermarks produced by pattern-embedding are visible, however.

The mapping from embedded data (either a symbol sequence or a pattern) to the arrangement of embedding primitives does not have to be straightforward. Scrambling the mapping, for example by

using a pseudo-random number sequence generated from a stego-key, could increase the security of the embedded data. In this paper, however, we will not discuss this and other methods of scrambling watermarks any further.

3. Embedding algorithms

This section describes, along with execution examples, algorithms that are created by combining the fundamental methods discussed in the previous section. In developing the following algorithms, we assumed that models were intended for viewing on 3D model browsers (e.g., VRML browsers).

All the algorithms are implemented by using a kernel for a non-manifold modeler [Masuda96]. The system employs a *radial edge* structure [Weiler86] to represent the topological relationship among vertices, edges, faces, and regions.

3.1. Triangle similarity quadruple embedding

A pair of dimensionless quantities, such as $\{b/a, h/c\}$ or $\{q_1, q_2\}$ in Figure 5, defines a set of similar triangles. The algorithm described in this section, which is called the Triangle Similarity Quadruple (TSQ) algorithm, uses such a dimensionless quantity pair as the geometrical embedding primitive to watermark triangular meshes. To realize subscript ordering, the algorithm uses a quadruple of adjacent triangles that share edges in the configuration depicted in Figure 6 as a Macro-Embedding-Primitive (MEP). Each MEP stores a quadruple of values $\{\text{Marker}, \text{Subscript}, \text{Data1}, \text{Data2}\}$. A marker is a special value (in this case a pair of values) that identifies MEPs. In Figure 6, the triangle marked M stores a Marker, S stores a Subscript, and D_1 and D_2 store data values Data1 and Data2. While each MEP is formed by topology, a set of MEPs are arranged by the quantity of subscript.

The TSQ extraction algorithm does not require an escrowed original cover-3D-model for extraction. However, it does require a pair of values that identifies marker triangles. Watermarks produced by the TSQ algorithm withstand translation, rotation, and uniform-scaling transformations of the stego-3D-models. The watermarks are resistant to resection and local deformation, since subscript arrangement and repeated embedding are employed. The watermarks can be destroyed by randomization of coordinates, by a more general class of geometrical transformation, or by extensive topological alteration such as re-meshing, among other disturbances.

The TSQ algorithm embeds a message according to the following steps.

- (1) Traverse the input triangular mesh to find a set of four triangles to be used as an MEP. In doing so, avoid vertices that have already been used for the watermark, or triangles that are unfit for stable

embedding, such as triangles whose dimension-less quantities are too small.

- (2) Embed the marker value in the center triangle of the MEP by changing its dimensionless quantity pair $\{e_{14}/e_{24}, h_4/e_{12}\}$, and thus the coordinates of its vertices v_1, v_2 , and v_4 , by small amounts (see Figure 6).
- (3) Embed a subscript and two data symbols in the remaining three triangles of the MEP by displacing vertices v_0, v_3 , and v_5 , which are not shared with the marker triangle in the center. Subscript is embedded in the pair $\{e_{02}/e_{01}, h_0/e_{12}\}$, and two data symbols are embedded in the pairs $\{e_{13}/e_{34}, h_3/e_{14}\}$ and $\{e_{45}/e_{25}, h_5/e_{24}\}$. For each of the three triangles, the algorithm first modifies the ratio h_i/e_{ij} by changing only h_i , and then modifies the ratio e_{ij}/e_{kl} while keeping the height h_i constant.
- (4) Repeat (1) to (3) above until all the data symbols of the message are embedded.

To embed multiple copies of the message, steps (1) to (4) are repeated many times. Figure 7 shows triangles that formed MEPs in darker gray. Owing to the mutual exclusion rule described in step (1) above, MEPs do not share vertices.

In steps (2) and (3) above, the magnitude of modification of the quantities must be larger than the expected noise. At the same time, it must be small enough for the watermarks to be unnoticeable by human beings when displayed by using a model browser. These minimum and maximum magnitudes of modifications are chosen as a result of a trade-off between robustness, space efficiency, and noticeability.

Given a watermarked mesh and two numbers that identify marker triangles, extraction proceeds according to the following steps:

- (1) Traverse a given triangular mesh and find a triangle with the marker, thereby locating a MEP.
- (2) Extract a subscript and two data symbols from the triangles in the MEP.
- (3) Repeat (1) to (2) above for all the marker triangles on a given triangular mesh.
- (4) Sort the extracted symbols according to their subscripts.

The TSQ algorithm performs a simple error correction by majority voting if multiple copies of a message are embedded.

Figure 8a shows a model of Beethoven's bust (4889 triangles, 2655 vertices) in which six identical copies of a message, each message consisting of 132 bytes, have been embedded by using the TSQ algorithm. The message was gradually lost when the model was resected by arbitrary planes (Figure 8b-c). As shown in Table 1, cutting the model in half left the entire message intact, and quartering the model left 102 out of 132 bytes intact. Since a subscript arrangement was used, intact characters still

tended to be in the correct positions within the message string.

Table 2 shows, for various models, their data capacities and execution times for embedding in the case of the TSQ algorithm. Times for extraction were not listed since they are about the same as those for embedding. The times were measured by using IBM AIXTM 4.1.4 operating system and a x1C c++ compiler on a 100 MHz PowerPC 604 processor.

The space efficiency in these examples is adequate for many practical applications. It should be noted, however, that these examples pushed space efficiency by sacrificing robustness to some extent. Increasing robustness, for example by increasing the number of repetitions of a message and using an error-correcting code, would reduce the effective data capacity.

Execution times are roughly proportional to the number of triangles in the models. The embedding algorithm was prototyped on a full-fledged non-manifold modeler kernel, which has many more features than necessary for the embedding algorithm. The times will improve significantly if the code is optimized for the embedding algorithm.

3.2. Tetrahedral volume ratio embedding

The ratio of the volumes of a pair of tetrahedrons is the embedding primitive for the Tetrahedral Volume Ratio (TVR) embedding algorithm described in this section. The algorithm is designed to accept triangular meshes as its input. It arranges the embedding primitives topologically into either a global or a local one-dimensional arrangement for symbol sequence embedding.

The TVR algorithm does not require a cover-3D-model for extraction. The watermarks that it produce survive affine transformation, but are destroyed by topological modifications such as re-meshing, randomization of vertex coordinates, and geometrical transformations more general than affine transformation (e.g., projection transformation), among other disturbances. A variation of the TVR algorithm discussed at the end of this section is resistant to resection and local deformation through the use of local arrangement and repeated embedding.

The TVR algorithm embeds data in accordance with the following steps. The crux of the algorithm is the establishment of a global one-dimensional arrangement of embedding primitives. Details of step (1) below will be explained later.

- (1) Find a spanning tree of vertices V_t , called a *vertex tree* [Taubin96], on the input triangular mesh M , given an initial condition I_{vt} for V_t . Convert V_t into a sequence of triangles $Tris$, called a *triangle sequence*.
- (2) Convert $Tris$ into a sequence of tetrahedrons $Tets$, called a *tetrahedron sequence*. To do this,

compute a common apex as the centroid of the coordinates of a few triangles selected from the triangle sequence (e.g., the first three). The selected triangles are removed from the triangle sequence so that their coordinates are not modified by embedding of symbols.

- (3) Convert *Tets* into a sequence of ratios of volumes *Vrs*. To do this, select the volume of a tetrahedron (e.g., the first one) in *Tets* as a common denominator of all the ratios, and use the volumes of the remaining tetrahedrons for numerators.
- (4) Embed a symbol into each ratio by displacing the vertices of the numerator-tetrahedrons. The vertex displacements for the current symbol must not interfere with modifications of the previously embedded symbols. (In Figure 9, triangles that are used for embedding, which are colored dark gray, do not share edges because of this constraint.)

We now explain details of the first step, starting with the method for creating a triangle sequence, and later come back to explain how to find an initial condition *Ivt*.

Generating a vertex tree *Vt* from an input triangular mesh requires that the input mesh be an orientable manifold. To generate *Vt*, traverse vertices from a given initial condition *Ivt*, that is, *{initial vertex, initial traverse direction}* pair, starting with *Vt* initialized to empty. At each vertex, by scanning the edges in counter-clockwise order, find an edge that is not a member of *Vt* and does not loop back to any of the vertices covered by *Vt*. If such an edge is found, add it to *Vt*.

In the example shown in Figure 10, the vertex tree has a root (and a branching point) at the vertex numbered 1. After passing through vertices 1 through to 10, the traverse backtracks to vertex 1 and adds two vertices, 11 and 12.

The vertex tree *Vt* is converted into the triangle sequence *Tris* as a set of edges *Tbe*, called a Triangle Bounding Edge (TBE) set is constructed. *Tbe* is initialized to a set of edges that connect vertices in *Vt*. To add an edge to *Tbe*, vertices are traversed according to *Vt*, starting from the root. At each vertex, all the edges adjacent to the vertex are scanned clockwise, and the scanned edge is added to *Tbe* if it is not a member of *Tbe*. A new triangle is added to *Tris*, which started as an empty sequence, if all three edges of the triangle are in *Tbe* for the first time and the triangle is not already in *Tris*. In the example shown in Figure 10, edges (except the initial entries of *Tbe*) are marked alphabetically in the order of their addition to *Tbe*, using alphabetical ordering. In the figure, members of *Tris* are marked with the numbers in circles according to the sequence in which each triangle is added to *Tris*.

As the initial condition, the TVR algorithm selects an initial *edge*, instead of *{initial vertex, initial traverse direction}* pair mentioned before. To select the initial edge, the algorithm computes, for every edge in the model, the volume of the tetrahedron subtended by the two triangles adjacent to the edge

(Figure 11). The algorithm selects, as the initial edge, the edge for which the tetrahedron's volume is largest. The reason why this method works is that affine transformation preserves inequality among volumes of tetrahedrons. (Note that these tetrahedrons are different set from the ones used to embed symbols.)

The TVR extraction algorithm employs the trial-and-error method to find a correct initial edge. The algorithm tries multiple candidate edges until it extracts a correct predetermined lead-in symbol sequence. This is because the edge found to have the largest volume may be incorrect owing to noise and other reasons.

Using an edge as initial condition leaves two equally possible alternatives in starting a traversal to construct a vertex tree. Again, this ambiguity is resolved by using the trial-and-error method. The TVR extraction algorithm extracts two sequences of symbols by using both alternatives. It then choose the direction that yields the correct predetermined lead-in symbol sequence.

Table 3 shows, for various models, the data capacity and the execution time for the embedding operation. The conditions for time measurements are the same as in Table 2. As with the TSQ algorithm, the amount of data that can be embedded by using the TVR algorithm appears to be adequate for many applications. The execution times in the same table show a similar tendency to those obtained with the TSQ algorithm; they are roughly proportional to the size of the model. They also leave room for a significant improvement through the design of an optimized code.

As mentioned before, the watermarks created by the TVR algorithm can be made resistant to resection and local deformation by using a local or subscript arrangement method combined with repeated embedding. The TVR algorithm strengthened by a local arrangement method called TVR Cluster (TVRC) embedding algorithm was used in the examples shown in Figure 12. To create sub-domains for local arrangement, this algorithm simply split the model into subsets (i.e., multiple disconnected meshes). Boundaries of subsets have duplicate vertices and edges so that cracks will not become visible. In this example, the message embedded in a model of a cow survived affine transformations. It also survived, to some extent, resections of a part of the model.

3.3. Mesh density pattern embedding

Another simple pattern-embedding algorithm, named Mesh Density Pattern embedding, generates polygonal mesh models given curved surface models as inputs. As the algorithm tessellates given curved surfaces, it embeds a visible pattern by modulating the sizes of triangles in the output mesh (Figure 13a). This pattern is hardly visible if displayed with a smooth shading (e.g., Gouraud shading) using proper

vertex normal vectors calculated from the original curved surfaces, but becomes visible when displayed by using wire mesh rendering.

This watermark withstands practically every geometrical transformation. The algorithm is resistant but not immune to polygonal simplification and other topology manipulations. Figure 13b shows an example of the effects of polygonal simplification in which the number of triangles in the original mesh has been more than halved by a polygonal simplification algorithm. The pattern will eventually be destroyed as a result of the simplification. However, a visible watermark may be just enough to deter unauthorized use of the data.

Note that many topological embedding methods can be combined with geometrical embedding methods. In fact, the “IBM mesh” model used in the examples of Tables 2 and Table 3 is the mesh shown in Figure 13a. Combining multiple embedding methods, each with its own strength and weakness, is a possible approach to increasing the utility of data embedding.

4. Summary and future Work

In this paper, we have introduced the concept of data embedding into 3D polygonal models. After describing the background and requirements, we argued that geometry is the best data type in a 3D geometrical model for embedding. Among many models of geometry, we chose polygonal model as the target of embedding for the study reported in this paper. We presented fundamental methods for embedding data into a polygonal model, namely, geometrical and topological embedding primitives and methods for introducing order into a set of modification primitives. Finally, we presented several simple data-embedding algorithms along with examples of their execution.

The algorithms described in this paper are merely examples of how to provide information channels in a 3D polygonal model. Some of them may be useful for inventory or for notifying cooperative users of the existence of copyright. However, they are not robust enough, for example, to prove that a theft has occurred. They lack many qualities, the most important of which is robustness, that are considered necessary for most applications of data embedding.

Development of more robust data embedding algorithms will be a focus of our future effort. Data embedding for 3D models whose intended purpose is not simple viewing is an interesting arena to explore. For example, Computer Aided Design models that are used for manufacturing may not tolerate vertex displacement. We also would like to widen the class of target objects for watermarking, for example, to include parameters defining curved surfaces and vertex normal vectors.

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List of figure and table captions

Figure 1. Three-dimensional models of dinosaurs in this simple scene are embedded with copyright notices and contact addresses, which can be extracted and displayed on demand.

Figure 2. Data embedding into 3D polygonal models.

Figure 3. Simple examples of topological embedding primitives.

Figure 4. Illustrations of examples of global, local, and subscript arrangements defined on a geometrical object.

Figure 5. Examples of dimension-less quantities that define a set of similar triangles.

Figure 6. A macro-embedding-primitive. In the figure, v_i are vertices, e_{ij} are lengths of the edges, and h_i are heights of the triangles.

Figure 7. A model watermarked by using the TSQ algorithm. Macro embedding primitives, each of which consists of four adjacent triangles, are shown in dark gray.

Figure 8. A model of a Beethoven's bust (4889 triangles) resected repeatedly by arbitrary planes.

Table 1. Data loss due to resection in the example shown in Figure 8.

Table 2. Model size, embedding data capacity, and execution time for embedding operation for the TSQ algorithm.

Figure 9 Triangles used for embedding by the TVR algorithm are shown in dark gray.

Figure 10. An example showing a vertex tree, a triangle bounding edge list, and a triangle sequence.

Figure 11. The volume of the tetrahedron a-b-c-d, subtended by two triangles a-d-c and b-c-d that are adjacent to the edge c-d, is computed. The arrows show two possible initial traverse orders from the edge c-d

Table 3. Model size, data capacity, and execution time for embedding operation for the TVR algorithm.

Figure 12. (a) Three-dimensional model of a cow (5804 triangles). (b) A message is embedded by using the TVR algorithm enhanced with local arrangement and repeated embedding.. The message survives (c) affine transformation or (d) resection.

Figure 13. Pattern embedding and effect of a mesh simplification algorithm on the embedded pattern. (a) Pattern is embedded by modulating mesh size by a factor of 1/4 (2996 triangles). (b) The mesh after polygonal simplification (1374 triangles).

Biographies

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figure 1

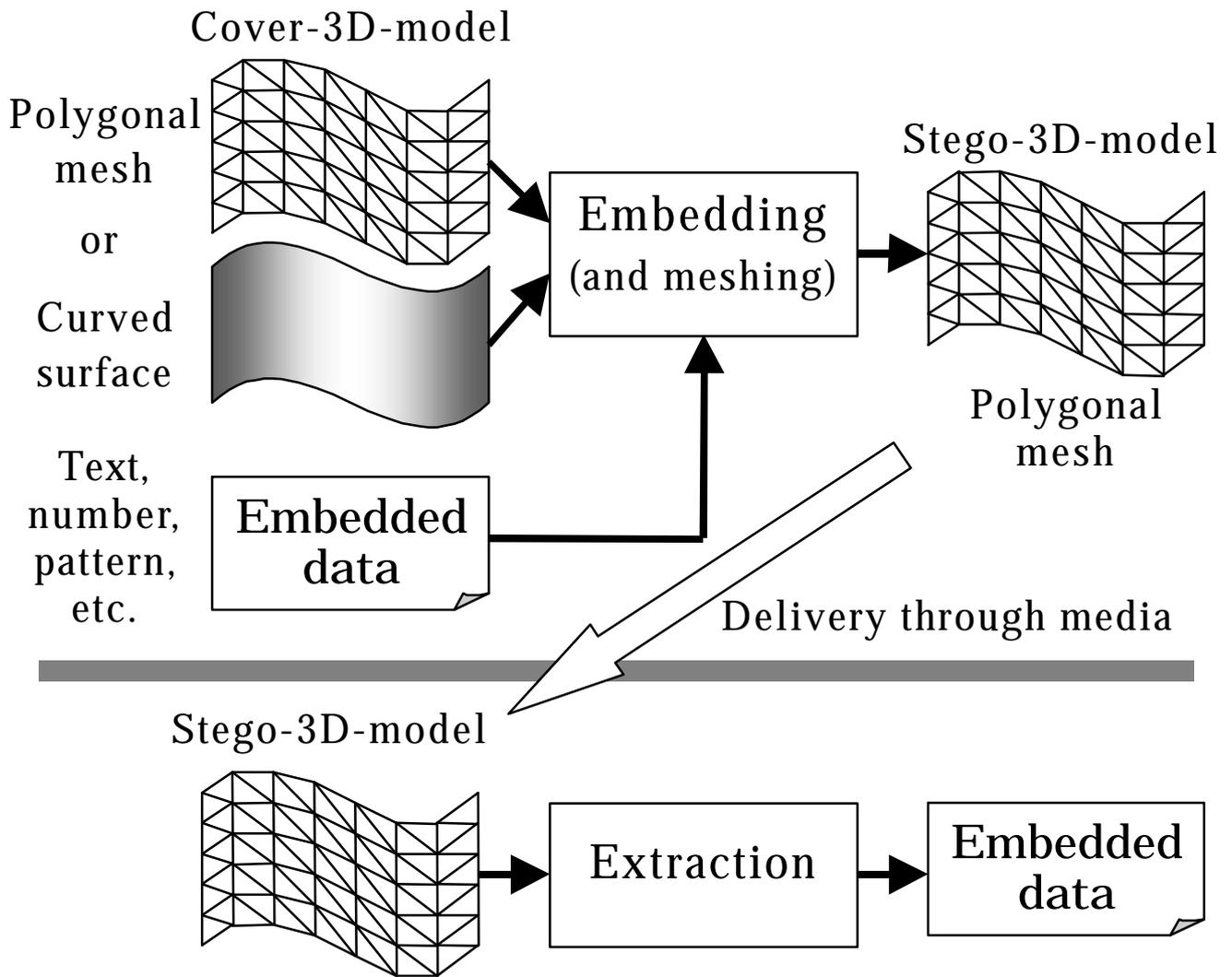


Figure 2

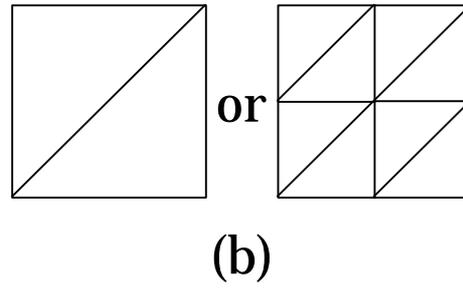
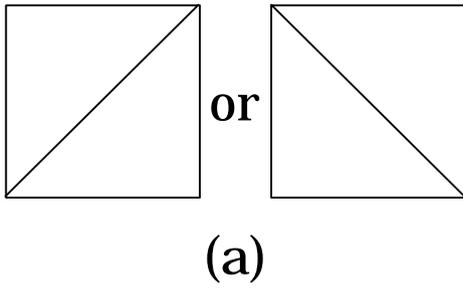


Figure 3

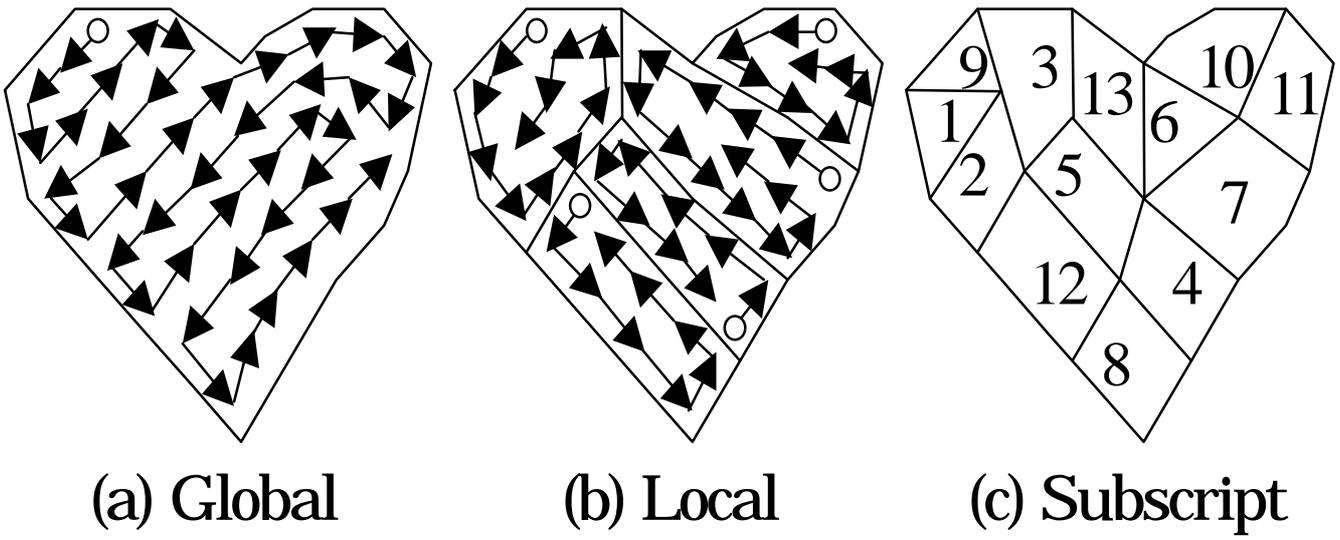


Figure 4

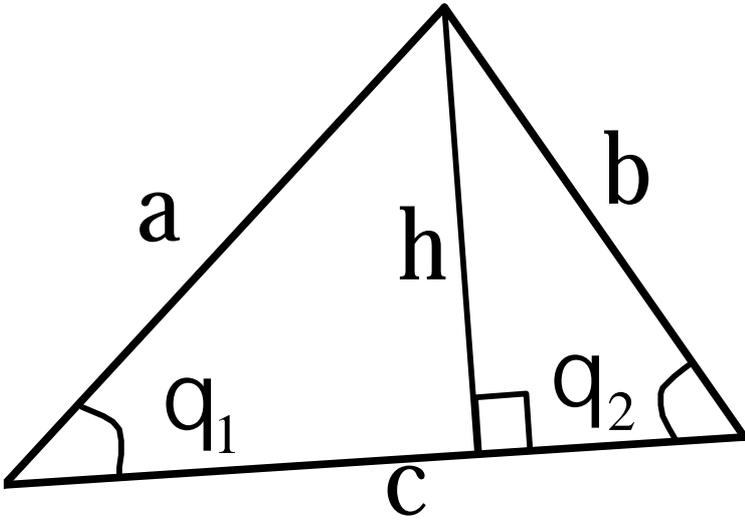


Figure 5

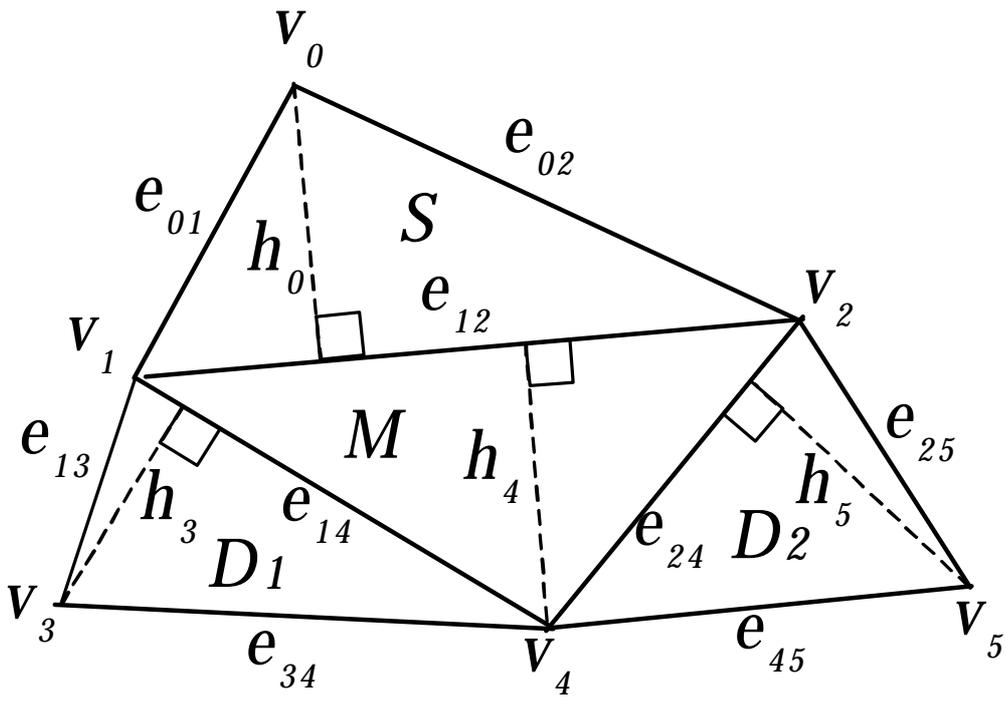


Figure 6

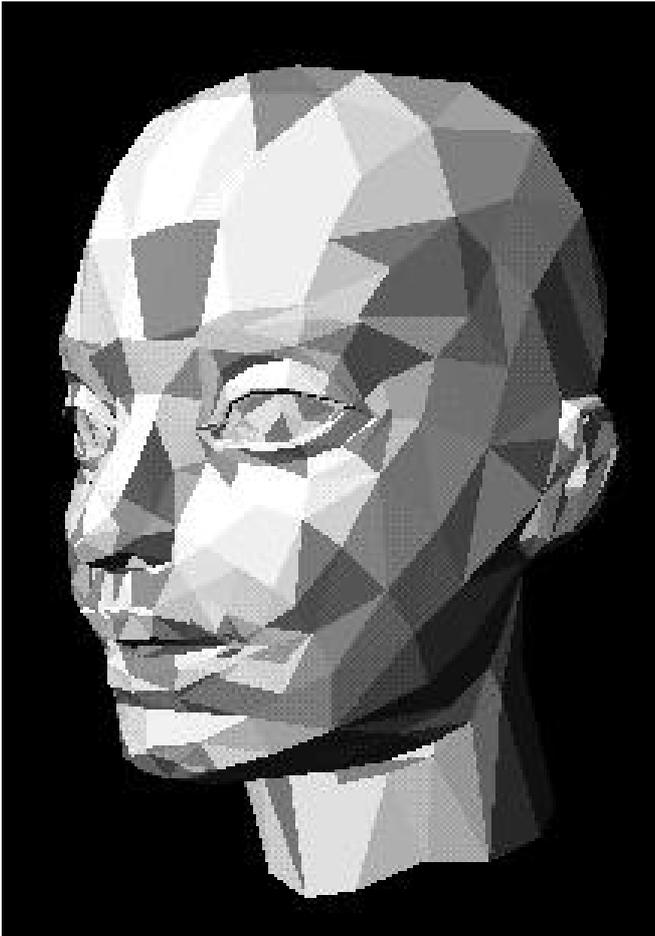
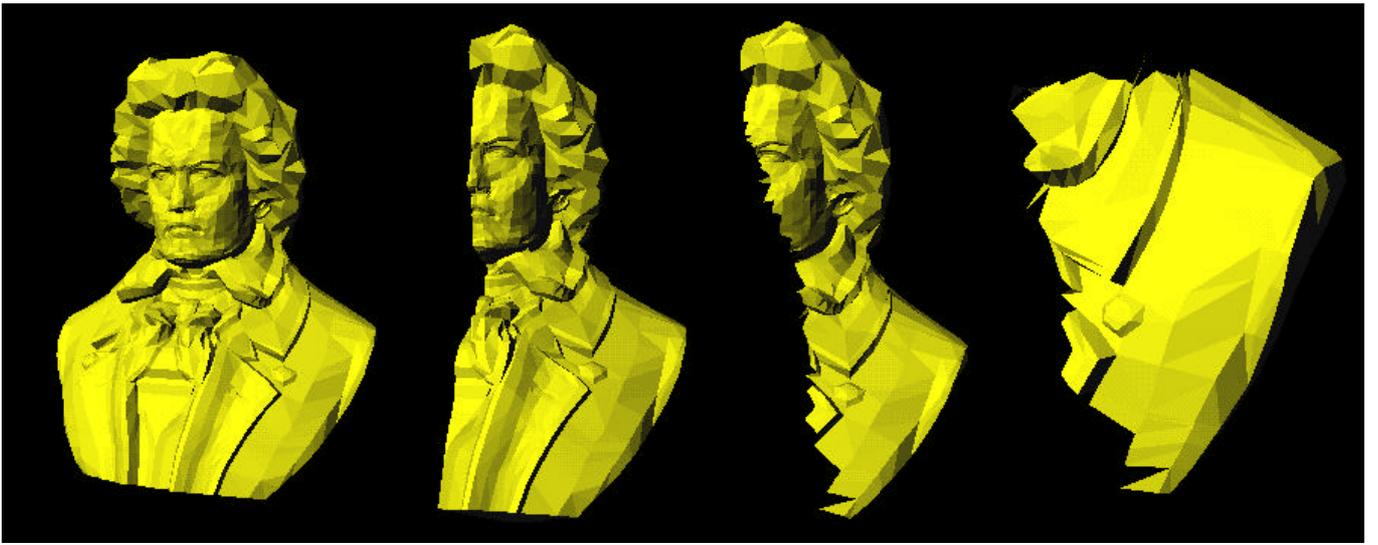


Figure 7



(a)

(b)

(c)

(d)

Figure 8

	Number of triangles	Data
(a)	4889	6 copies, 132 bytes each
(b)	2443	132/132 bytes
(c)	1192	102/132 bytes
(d)	399	85/132 bytes

Table 1

Model	Number of triangles	Data capacity per model [bytes]	Embedding execution time [sec]
Cow	5804	1062	19.8
Triceratops	5604	966	9.9
Beethoven	4889	873	9.7
IBM mesh	2996	486	9.8
Face	1406	210	2.3
Stegosaur	1023	180	2.5
Sphere	959	132	1.4

Table 2

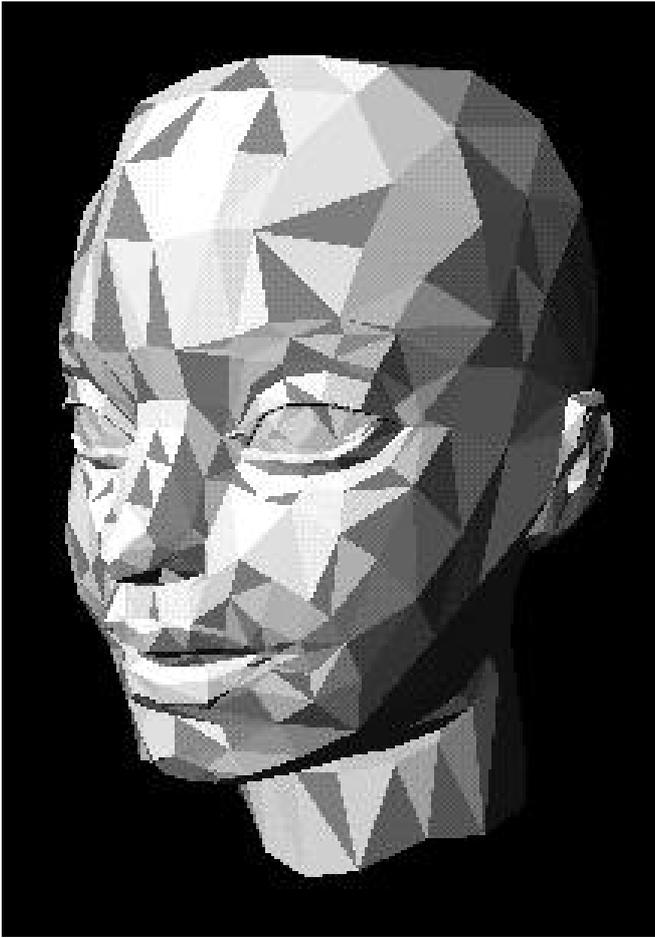


Figure 9

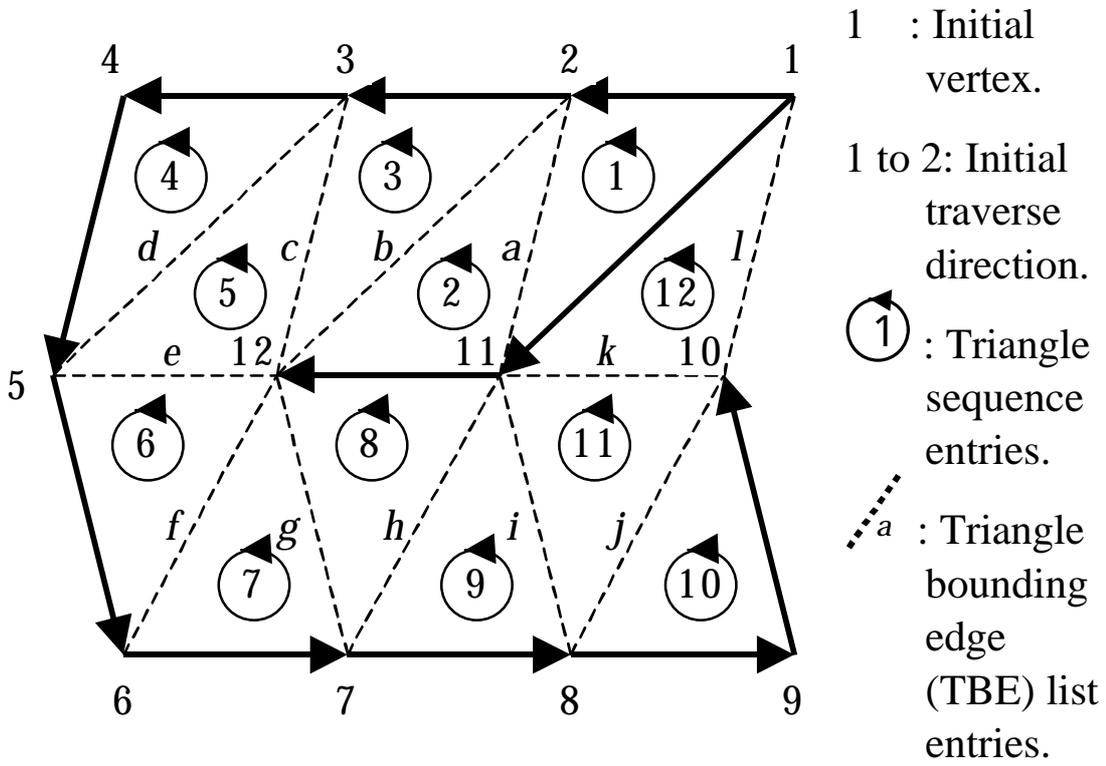


Figure 10

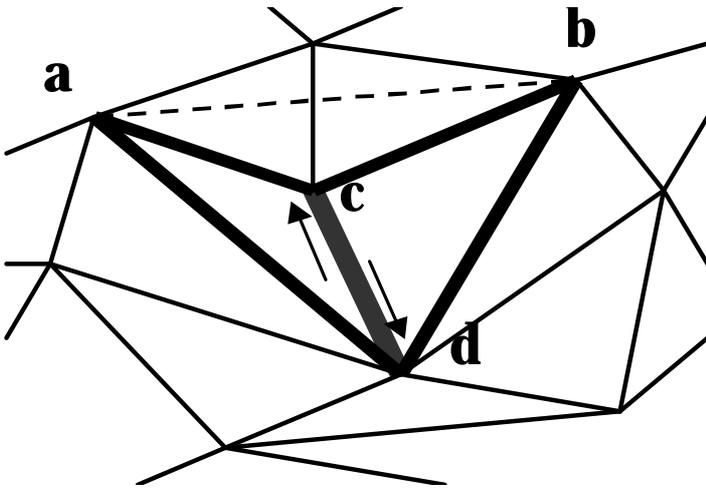


Figure 11

Model	Number of triangles	Data capacity per model [byte]	Embedding execution time [sec]
Cow	5804	1027	20.2
Triceratops	5604	650	7.2
Beethoven	4889	324	9.6
IBM mesh	2996	652	9.9
Face	1406	116	2.2
Stegosaur	1023	225	2.4
Sphere	959	216	1.5

Table 3

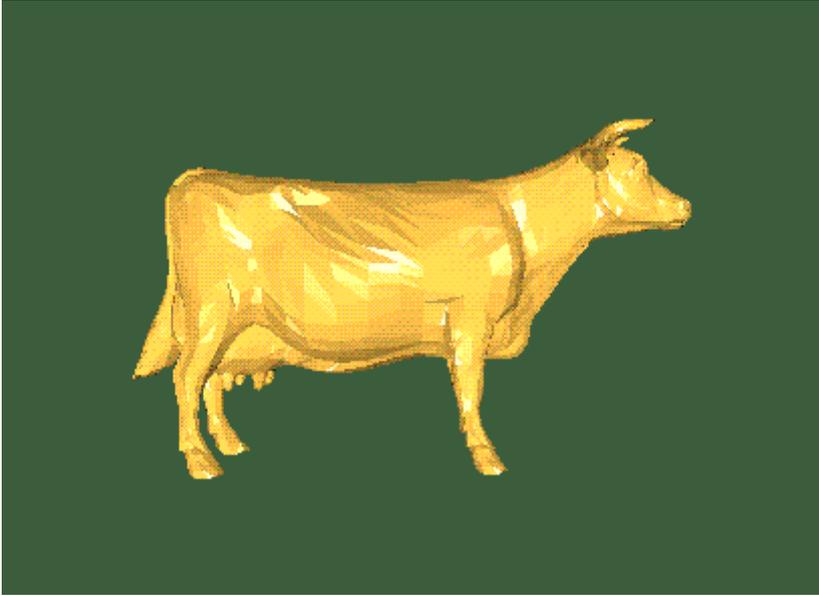


Figure 12a



Figure 12b



Figure 12c



Figure 12d

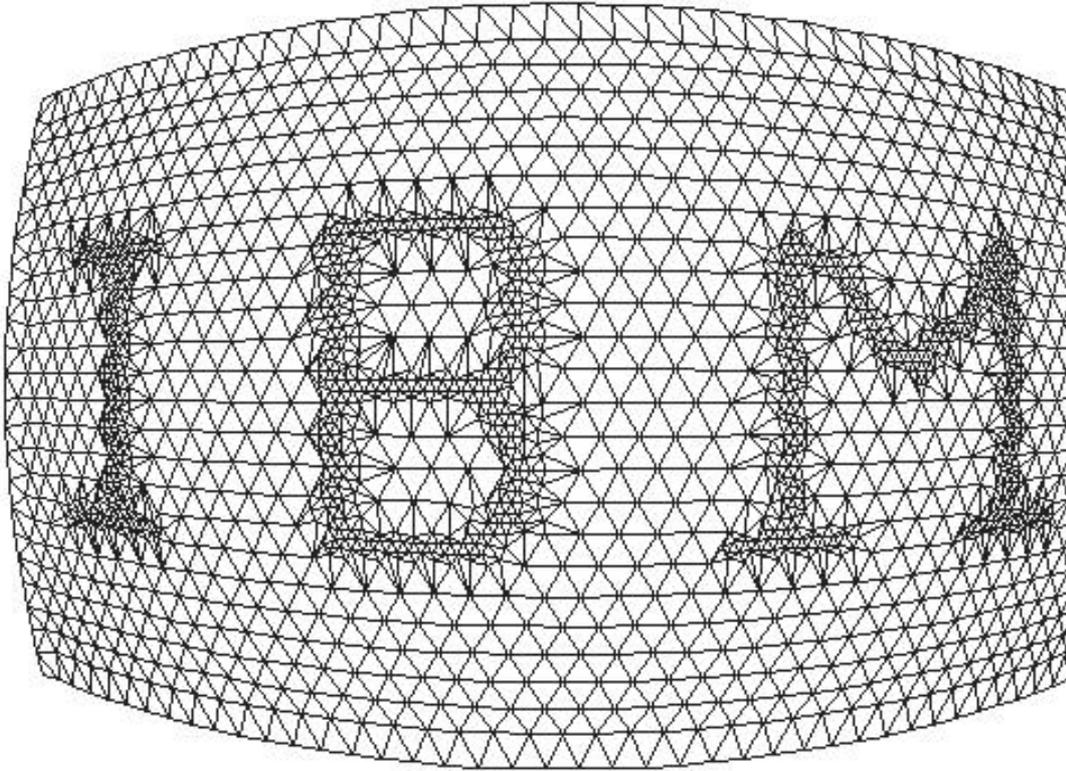


Figure 13a

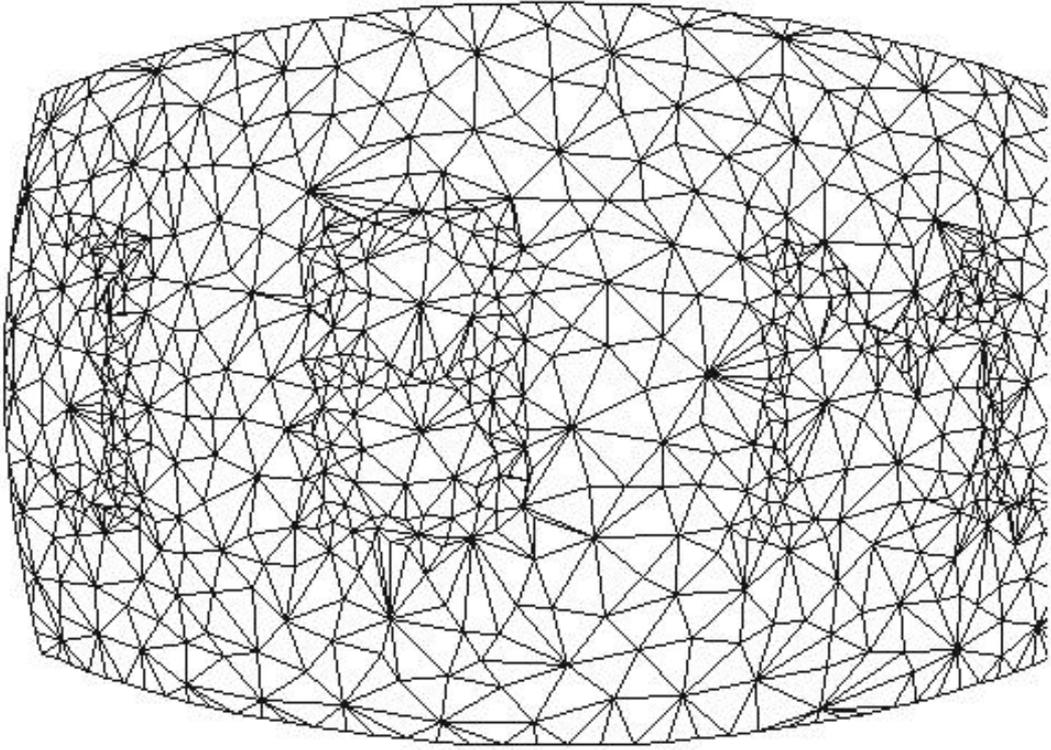


Figure 13b