3-D Surface Reconstruction by the Means of Evolutionary Algorithms

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Abstract. In the paper we propose a new method for an isosurface construction from unorganized points in 3-D. The aim is to combine evolutionary algorithms with a recursive subdivision scheme. The algorithm starts from a base population where each individual represents an N-level surface approximation of an input object. Next, the population is evaluated and an offspring generation is created with a denser subdivision of a surface. The method is illustrated by a set of samples.

1 Introduction

1.1 Problem definition

Surface reconstruction of 3-D objects (also known as the problem of recovering 3-D shape) may be classified to NP-hard class algorithms [1] and became a significant issue in geometric modelling in recent years. In general, the problem may be stated as follows: For a given set of P points sampled from an unknown surface U (in 3-D), create a surface model S best approximating U (Fig. 1). Moreover, it is assumed that the set of P points is unorganized and might be noisy (which means that some of points in the input set may not necessary belong to a surface). The surface U is arbitrary of unknown topological type and may possess sharp features like creases and corners. Therefore, an algorithm must infer with geometry and topology of reconstructing object.

In recent years, the importance of surface reconstruction increased due to wide-spreading of 3-D laser scanners and its applications in many commercial and scientific areas. In fact, 3-D scanning is a process of reverse engineering of physical object into shape, colour and material. This paper discuses only the first of these three properties of an object.

On the whole, three-dimensional objects are represented by triangles (the simplest co-planar figure in 3-D space). Hence, the process of transforming discrete point data to triangles is called triangulation. Moreover, they are arranged in a clockwise or a counter-clockwise order.

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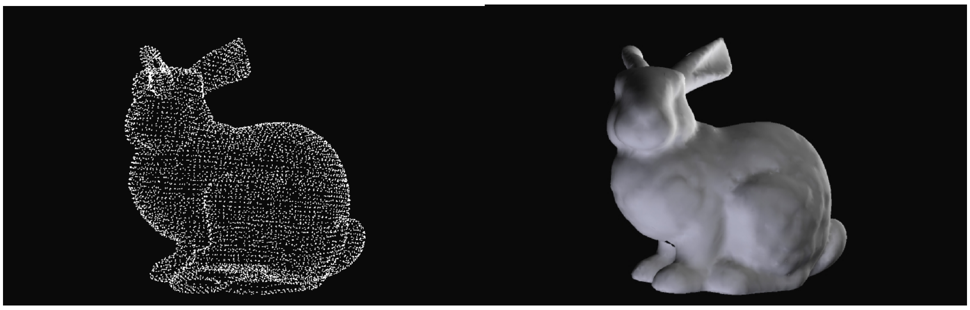

Figure 1. Reconstruction problem. On the left – a set of 3-D points P, on the right - surface S.

1.2 Possible applications

The reconstruction of 3-D shapes has numerous applications in areas that include:

- Medicine – it is used in magnetic resonance (MR) and computer-aided restoration design [12].
- Archaeology – 3-D documentation of historical objects, virtual galleries and museums [7].
- Science – constructing a surface of procedurally generated objects (e.g. fractals), visualization of objects and results.
- Films and TV – real persons may be reconstructed and represented in a virtual environment. Also applied in special effects.
- 3-D printing – recreating virtual objects.
- And others.

2 Previous work

2.1 3-D surface reconstruction

The 3-D reconstruction of volumetric data sets has been in use for several years and has its representation in extensive literature [2, 4, 8]. Most of all reconstruction algorithms are deterministic ones and work off-line. Moreover, none of these methods may claim robustness for all kinds of input data. In most cases performance of the algorithms depends on sample objects.

In recent time, due to increasing processor power more consideration is given to intelligent computation methods. Most attention is paid to neural networks [5, 16] and evolutionary algorithms [13, 14]. Especially, methods discussed in [9, 3, 11] seems to be very attractive to apply in the 3-D surface reconstruction problem.

The authors of [13, 14] use Simulated Annealing, Genetic Programming and Evolution Strategy (also hybrid of these two) to surface reconstruction problem. In most cases their algorithms initially start from reduction of input points. Then population is set on the data, where each individual represent a point in the search space. Delauney triangulation is applied in the initial stage to make interconnections between vertices. Then quite primitive mutation and recombination operators are applied. The methods lack of strong quality criterion and directed mutation and recombination. Moreover, results depend on the initial step (using deterministic

algorithms) in a large extend. The algorithm manages with 3-D data but in a 2.5-D space (result of Delauney triangulation), which simply make it difficult to apply to real data.
The similar idea to the aforementioned one is presented in the work of Kodama [6]. A genetic algorithm is applied to data from a scanning electron microscope.

2.2 Contribution

The algorithm presented in the paper offer the following benefits:

- creating more natural-looking meshes, where primitives may not necessarily equally be distributed over input data,
- noise reduction in input data, where unwanted points will be omitted in a final object,
- new quality criteria of reconstructed objects are introduced,
- create meshes with Level of Details referring to a surface,
- lacks and holes in input data may be reconstructed.

3 Isosurface construction

3.1 Algorithm overview

We propose a new surface reconstruction algorithm combining subdivision surfaces [10, 15] and evolutionary algorithms. The input of the algorithm is a set of 3-D points describing an object. Population consists of meshes that approximate an input surface U. Initially, an individual is a deformed cube bounding an object (Fig. 2). Every next generation gives a closer approximation of an object by subdivision scheme. We use the *1+λ* and *Evolutionary Search* algorithms, with proportional tournament selection type. Also, mutation and recombination operator are applied.

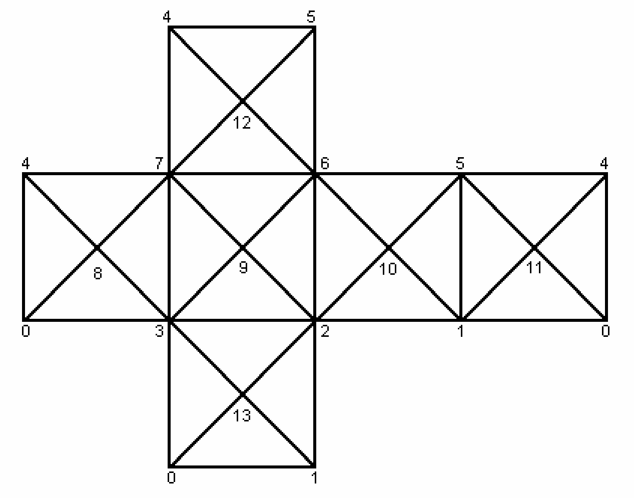

Figure 2. Initial mesh.

In general, the algorithm may be written in the following form:

1. Initiation – base population of deformed cubes
2. Repeat until assumed refinement level reached (no. of subdivisions)
    a. Meshes quality estimation
    b. Selection (best individual or tournament selection). Meshes best approximating a surface should probably be chosen at this refinement level
    c. Subdivision process (a number of triangles in every individual increases)
    d. Mutation and/or recombination.

3.2 Algorithm details

Initial population

A genotype of an individual is a bounding box of the search space. During initiation, a mesh consists of 14 vertices and 24 triangles (Fig. 2). Every vertex of the cube is randomly ascribed to a point from an input set, creating a phenotype of an individual. There are two methods of picking points up at this level. One of them is tournament selection with proportional probability to the distance to a top vertex. The other one chooses points randomly but only from a closer quarter of a box. The points that have been selected to a mesh are removed from an input set. At the end of this process, our population consist of deformed cubes over sampled points.

Offspring generation

Two methods of mesh refinement are used. They differ in the manner of introducing new triangles to a surface. The Ternary Subdivision scheme and Isotropic Template were chosen for mesh refinement process. They are depicted in Fig. 3. Depending on the scheme there are different point selection methods. The general idea is based on a sphere anchored at a given point limiting the search space. New points are inserted to a mesh in a stochastic manner with a tournament selection scheme. Probability of point selection is proportional to the distance from a centre of a sphere. Chosen points are removed from a search space. A sphere radius depends on a subdivision scheme. For Ternary Subdivision sphere radius is equal to an inscribed circle. On the other hand, in Isotropic Template radius is limited to the length of closest vertex.

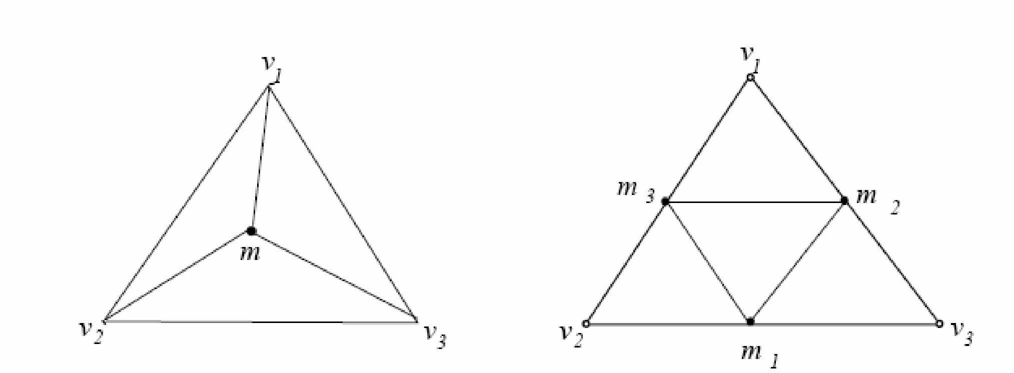

Figure 3. Ternary Subdivision (left) and Isotropic Template (right).

Quality criteria

Present research has not been paid much attention to quality criteria of reconstructed meshes. Results of deterministic algorithms are compared visually or to objects of known shapes (like a procedurally generated sphere or a cone). Therefore, it is difficult to evaluate an object from the simple fact that the reconstructed mesh approximates an unknown surface (what is assumed in the definition). However, we have introduced new quality criteria for objects:

- Evaluation by point cloud – number of points from a search space that bounding spheres may encompass.
- Evaluation by C1 continuous – minimize of maximum curvature of a mesh.
- Evaluation by standard deviation – a standard deviation of average edge length.
- Evaluation by variance – variance of average length of edges in a mesh.
- Evaluation by largest distance – difference between the lengthiest edge and the shortest one.

Mutation operator

The implemented mutation operator is directed and include up to 3% of mesh points of an individual. Triangles with most obtuse angles are mutated by randomly selecting new points from a nearest neighbourhood.

Recombination operator

Recombination of two individuals randomly exchanges points of appropriate triangles. Up to N-points may be selected (where N denotes number of points in a mesh). The two surfaces must be comparable (consist of a same number of vertices and faces) which present difficulty with this operator.

4 Experimental results

A prototype application was written in C++ using Win32 API. The application was running on standard off-the-shelf PC's (Intel Pentium Mobile 1.8 GHz and Intel Core Duo 2.4 GHz with 1 GB of RAM). The visual results are shown in Figs. 3–5. Tables 1–2 depict the sizes of tested data and corresponding execution times in the above hardware and software configurations.

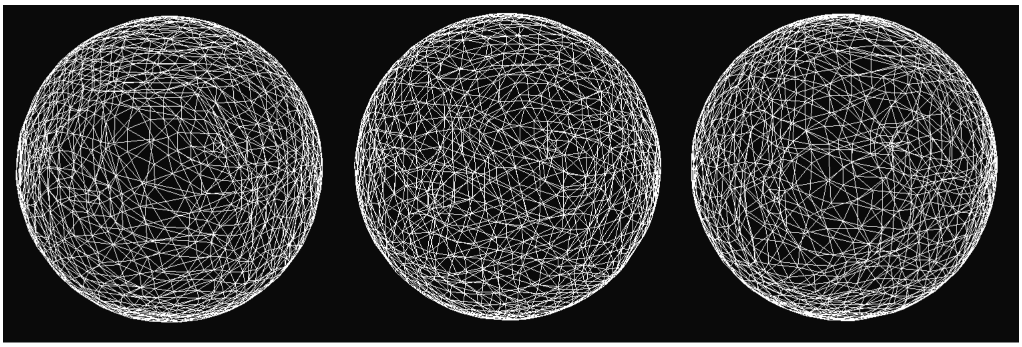

Figure 4. Sphere reconstruction - different individuals at Level 3.

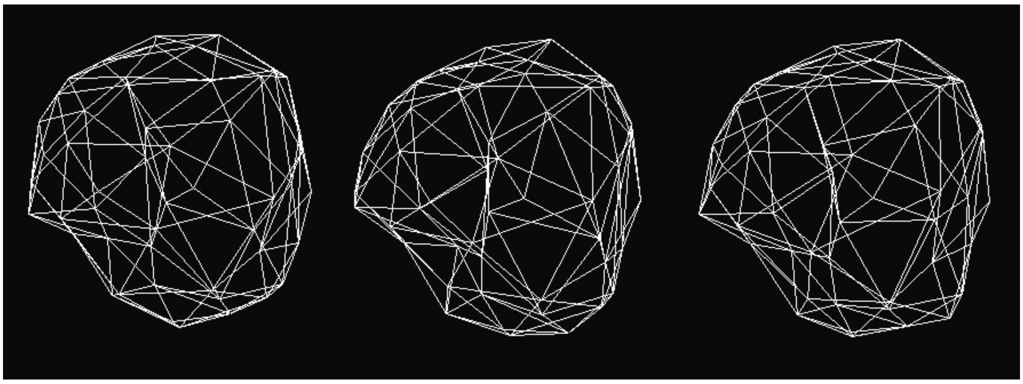

Figure 5. Igea model – level 2 of mesh refinement (different individuals).

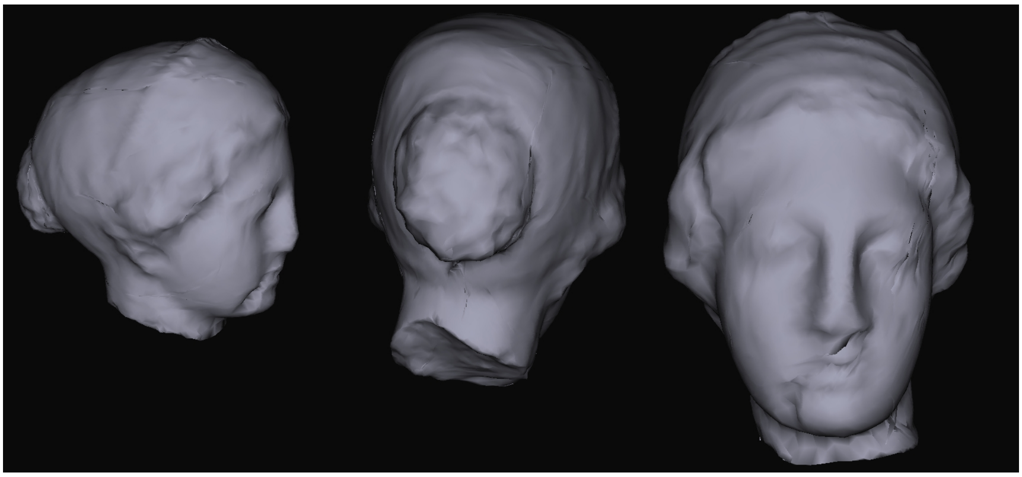

Figure 6. Igea model (also known as Venus) – rendered (level 5). One individual from the population. Note that the crease on the chin is a part of the object.

Table 1. Sphere reconstruction. Population size set to 20.

Refinement level	Approx. Time	No. of faces for one individual
Level 1	< 1 sec	72
Level 2	< 1 sec	216
Level 5	10 sec	5832

Table 2. Igea model reconstruction. Population size set to 120.

Refinement level	Approx. Time	No. of faces for one individual
Level 1	2 sec	24
Level 2	6 sec	96
Level 3	4 minutes	384
Level 4	16 minutes	1536
Level 5	54 minutes	6140

At present, it is difficult to compare computation times of this algorithm to other ones. As it was aforementioned there are no other stochastic algorithms of this form. Despite this, we may quote some results. The reconstruction process of Igea model takes approx. less than 10 seconds using one of the fastest deterministic algorithms [10]. Obviously, it is hard to compare just times of these two algorithms. On the other hand, results presented in [14] were obtained in a 24-hours continuous process.

5 Conclusions

Volumetric graphics have been rapidly developing over the past years. Popular PC-based systems offer more efficient CPUs and accelerated graphics boards capable of a real-time visualization of large sets of polygon mesh models. In the paper we have shown that from an unorganized data set, an isosurface with a hierarchical mesh can be created in the stochastic manner. Our population starts from a low-order polygon, set recursively, applying wrapping-like displacement of newly added vertices. The refinement process reconstructs the isosurface to a given resolution by a set of individuals. Moreover, we have introduced new quality criteria for meshes which have not been previously advanced.

Our results are promising although the algorithm still requires improvements. Especially, the point selection scheme and the recombination operator have some minor drawbacks.

Finally, the time in the surface reconstruction process is not decisive and almost all of the present algorithms are off-line.

6 Acknowledgments

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7 Bibliography

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