IMPROVED ATOMIC MESHES FOR 3D SEISMIC DATA

José Marcos Pilato Jr
Paulo Roma Cavalcanti
Claudio Esperança
Antonio Alberto Fernandes de Oliveira
Laboratório de Computação Gráfica, Universidade Federal do Rio de Janeiro
COPPE/Sistemas and Department of Computer Science
Rio de Janeiro - RJ - Brazil
{*pilato, roma, esperanc, oliveira*}@*lcg.ufrj.br*

Abstract. *This work extends to 3D the "Improved Atomic Meshes" methodology, which creates numerical meshes from 3D seismic data. The main goal is to produce numerical meshes from image data "directly", bypassing any image segmentation step.*

Traditionally, seismic data must first be examined by geologists and geophysicists who, in turn, model the fundamental geometric shapes, i.e., horizons and faults. This model can then be used to generate discrete meshes for several kinds of numerical simulations, such as a reservoir simulation, the propagation of acoustic waves, or large-scale fluid and heat flow within saturated porous sediments. The implemented technique generates tetrahedral meshes directly from the seismic image datasets, by combining image processing and physical modeling. Instead of being obtained from an intermediate geometrical model, horizons and faults are extracted and visualized directly from the 3D mesh.

The proposed method begins by enhancing features in the image, and generating an initial distribution of points (atoms) over the domain of the model. Afterwards, the atoms are projected onto perceived features and a potential energy is assigned to the image pixels and to the set of atoms. Finally, the atoms are moved to a configuration of minimum potential energy, and a mesh is generated by means of a Delaunay triangulation.

A prototype of this method was implemented, and several tests to evaluate the mesh quality, and the degree of conformance to the original data, were conducted.

Keywords: *Improved Atomic Meshes, Numerical Meshes, Seismic Data*

1. INTRODUCTION

Creating meshes which approximate or are in some way conformal to the features of a given image has captured the attention of many researchers over the last years. The idea is that the resulting mesh contains much of the information of the underlying image which makes it ideal for applications such as image compression, image modeling, medical image analysis and others (J. Lee, 2000).

A particularly interesting application is the creation of meshes from seismic images. The simulation of complex geological processes such as the evolution of sedimentary basins and multiphase fluid flow within sediments is important for decision-making processes in the oil industry. In oil exploration and production, critical decisions are made based on the results of reservoir-scale or basin-wide simulations. The quality of these simulations is directly dependent on the accuracy of subsurface earth models.

The drilling of a wildcat well can cost between $ 5 to 50 million USD. The worldwide success rate of these wells is on average less than 10% (Lerche, 1997). In known petroleum reservoirs, an average of 40% is recovered or produced, whereas about 35% of the oil is usually left in place due to rock-fluid interaction forces. The remaining 25% can be potentially recovered and may represent a sizable increase of assets for oil companies if new technologies, to identify and produce these resources, are made available (Lou et al., 2005).

One of the major causes of the relatively poor performance in wildcats is the limited knowledge of the physical and geometrical characteristics of earth models. The construction of earth models is a phenomenal problem not only due to the scarcity of data but because of the geometrical complexity of geological structures. The major sources of subsurface data comes from wells and from interpretation of the acoustic response to seismic waves. This data is very patchy in nature and provides a limited amount of information for building the earth model "puzzle".

Traditionally, the geological interpretation of seismic data results in a set of curves and surfaces, which are used to construct a consistent earth model. This model can then be used to generate discrete meshes for several kinds of numerical simulations, such as a reservoir simulation, the propagation of acoustic waves, or large-scale fluid and heat flow within saturated porous sediments.

The geological model must contain all of the geological features, such as horizons (separating surfaces between geological layers) and faults (discontinuities caused by the brittle behavior of rocks when subject to tectonic stresses), as can be seen in Figure 1. Horizons and faults compart the geological model in a set of regions of the space, the union of which generates the layers. The geological model is used to create a numerical mesh, which contains the boundary of the model. Horizons and faults are represented as faces of tetrahedra in 3D, or edges of triangles in 2D.

At present, geological models are obtained by integrating various sources of data, including seismic interpretation performed by humans, who define the fault planes and horizons interactively. A different approach, created by Hale (2001, 2002), adapts image processing techniques and physical modeling, in order to create meshes (containing horizons and faults) directly from seismic images, without creating an intermediate geometric model.

The process begins by enhancing features in the image, and generating an initial distribution of points (atoms) over the domain of the model. Then, it associates a potential energy to the image pixels and to the set of atoms. Finally, the atoms are moved to a configuration of minimum potential energy, and a mesh is generated by means of a Delaunay triangulation. Therefore, image segmentation is never executed *per se*, but since the atoms tend to adhere to regions of higher contrast, a sort of "implicit" segmentation is achieved. Moreover, no horizons or faults are ever identified and the Delaunay triangulation is not constrained.

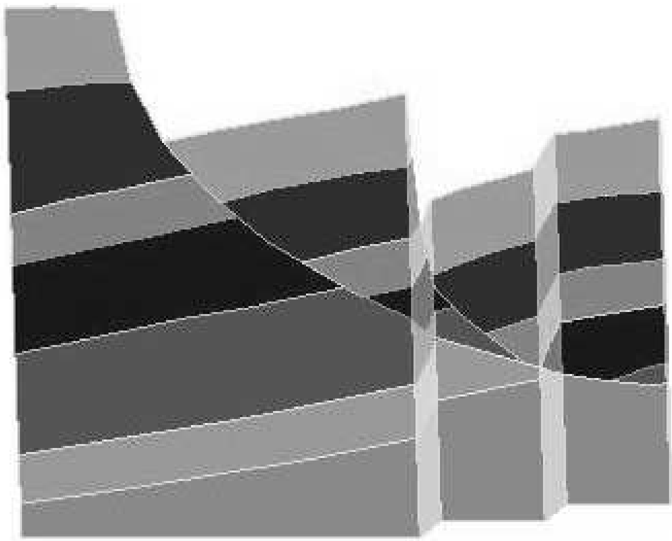

Figure 1: Horizons and geological faults.

In this paper we extend to 3D the Improved Atomic Mesh technique (Esperança et al., 2007), which was based on Hale's Atomic Meshes (Hale, 2001). Improved Atomic Meshes has two main advantages over the original Atomic Meshes: (1) an atom projection process whereby atoms are initially placed on perceived image features and (2) a modification of the energy field formulation by including a new term related to the Laplacian coordinates of mesh vertices. The purpose of these enhancements is to obtain a more conformal mesh (i.e., better adapted to image features) composed of better shaped triangles.

2. RELATED WORK

A seismic image is the result of seismic processing techniques. It represents the result of the convolution between the energy source and the rock impedance contrasts. Geologists extract geological features from this data. Some of these structural features can be represented as curves and surfaces, which act as layer boundaries. Several physical models have been proposed recently, which aim at computing optimal positions for points on those boundaries, producing good results (Jalba et al., 2004; Costa, 1999; Shimada, 1993; Garcia et al., 1992).

Active contours (Kass et al., 1988) – commonly known as "snake" models – for instance, are a class of algorithms known to properly segment images in many applications where the boundaries are not well established. However, they are not suitable to seismic images due to the large number of thin and disconnected features typically present. A different snake should be initialized for each region delimited by a set of linear features. As some of the regions have complex shapes, including narrow bottlenecks, it is not possible to guarantee that long extensions of the feature borders are not lost at the end of the process. Moreover, even if topologically adaptable snakes (McInerney and D.Terzopoulos, 1995) (implicit or not) are used, it is likely that different features are aggregated in a same contour. A post-processing is then required to separate them, in this case. The snake displacement in a given step must also be small enough so that it does not not jump over a whole feature, which slows down the process.

J. Lee (2000) introduced a technique aimed at producing meshes directly from images. The proposed approach employs the Floyd-Steinberg method, a classical error-diffusion algorithm for image halftoning, to distribute the mesh nodes in the domain of an image based on its gradient magnitude.

As an alternative, Hale (2001, 2002) proposes a framework known as *Atomic Meshes* wherein individual particles – or atoms – are attracted to the features of interest by means of an energy field formulation. This approach is more suitable to seismic images since it does not try to approximate features with closed curves, but only to place atoms fairly close to them. The algorithm can be summarized by the steps below:

a) Image pre-processing for suppressing out much of the noise and enhancing the main features, e.g., faults and horizons in a seismic image or bones and organs in a medical image.

b) Generation of an initial set of atoms distributed in a quasi-regular manner on the image space.

c) Minimization of the total potential energy function.

d) Generation of a Delaunay triangulation using the atoms as vertices.

The key merit of the Atomic Mesh approach is that the mesh creation process is stated as an energy minimization problem. This is described in some detail in Esperança et al. (2007).

The main ingredient for obtaining good results is to start with a fairly well-processed seismic images so that the features correspond to areas of high contrast. This is due to the fact that the image energy is computed merely as proportional to the pixel values.

A different approach was presented by Machado (2008), who introduced the Open Neural Meshes, a competitive learning algorithm, which builds a mesh, by means of a probability function, with the topology of an open surface without holes.

3. EXTENSION TO 3D

The Improved Atomic Meshes approach can be naturally extended to 3D, by just adding a Z coordinate to all of its equations. However, a few details require some special treatment.

3.1 Image Processing

This step of the algorithm aims at enhancing the features of interest. In the case of seismic images, these correspond to borders between layers or faults (horizons).

In 3D, the input data is a set of colors defined for each point (x, y and z) of a regular grid. Therefore, we may think of the 3D image as a cube, and fixing one of its coordinates results in a set of 2D images. Since any kind of border enhancing filter could, in theory, be used, we chose to apply the same modified Sobel filter presented in Esperança et al. (2007) on each image of the image set, i.e., the Sobel filter is run for each constant-Z “slice” (2D image) of the cube, as illustrated in Figure 2.

3.2 Atom Distribution

Hale (2001) proposed an algorithm to produce a pseudo-regular atom distribution, in such a way that the atoms are uniformly placed near the features of the image.

In 3D, on the other hand, we had to place additional atoms on the border of the image cube. These “border” atoms do not contribute to the Atomic Potential Energy, nor move during the optimization process. The only purpose of these special atoms is to guarantee that the final triangulation has a shape similar to that of the input data. In other words, border atoms anchor

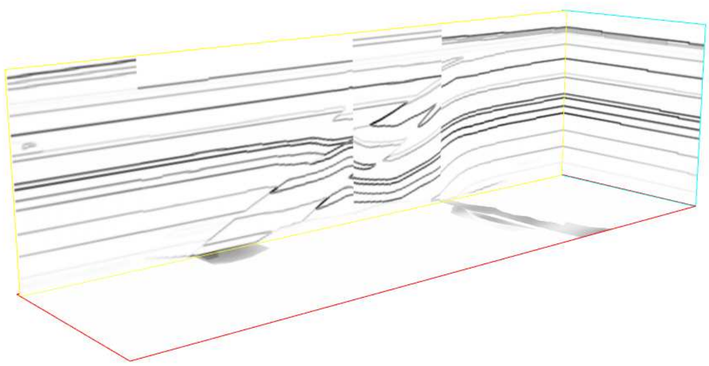

Figure 2: Image Processing.

the external shape of the triangulated volume. It should be noted that regular atoms are never placed near the cube faces so as to avoid bad elements in the final mesh.

The initial atom placement in Hale's original approach is controlled by an input scalar field $d(x)$ called *nominal distance*. This parameter indicates the "desired" average distance between mesh vertices. In 3D, atoms are initially placed at each vertex of a regular tetrahedral mesh with edge length $\sqrt{9/24}d(x)$, i.e., the ratio between the radius and the edge of a regular tetrahedron.

After creating the atoms inside the image, regularly spaced border atoms on each face of the image cube are created by a 2D algorithm. Figure 3 depicts this process.

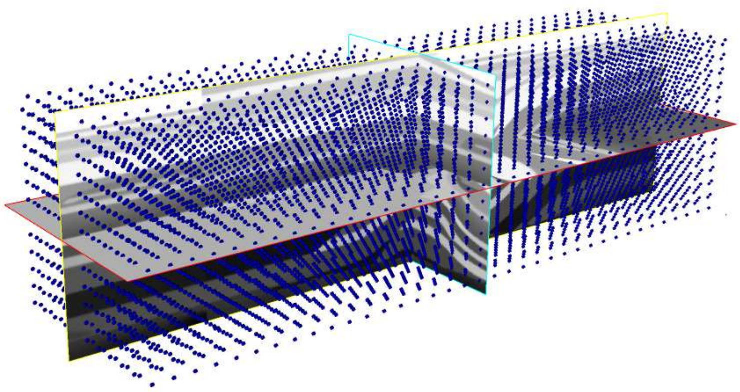

Figure 3: Atom distribution.

3.3 Atom Projection

Before applying the optimization algorithm, the atoms close to the features of the image are projected, as shown in Figure 4. This scheme aims at enhancing the initial atom placement step by means of a projection procedure whereby atoms are explicitly moved to features in their neighborhood. A "feature pixel" is characterized by having a gray level below a certain threshold value $\epsilon \in [0, 1]$. The main difficulty in this step is ensuring that no two atoms are projected too close to each other.

The procedure is described in detail in Algorithm 2 of (Esperança et al., 2007) and can be applied to 3D with almost no modification other than replacing the 2D limit distance of $\sqrt(3)/3d(x)$ by its 3D equivalent $\sqrt{9/24}d(x)$. Figure 4 shows the effect of the atom projection step in our sample seismic data set.

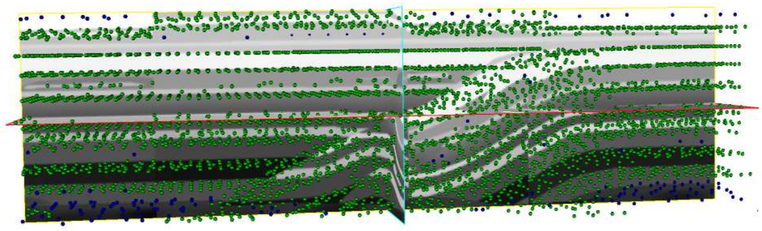

Figure 4: Projected Atoms.

3.4 Mesh Optimization

The remaining steps leading to the mesh construction are kept unchanged. In particular, we employ the same energy formulation described in the original Improved Atomic Meshes paper. Define the laplacian of a given mesh vertex v_i as

$$\mathcal{L}(\mathbf{v}_i) = \mathbf{v}_i - \frac{1}{|\mathcal{N}(\mathbf{v}_i)|} \sum_{\mathbf{v}_j \in \mathcal{N}(\mathbf{v}_i)} \mathbf{v}_j, \tag{1}$$

where $\mathcal{N}(\mathbf{v}_i)$ represents the set of all edge neighbors of $\mathbf{v}_i$. Then, the mesh optimization consists of minimizing the total energy $P = \beta A + (1 - \beta)B$, as per Hale's original method, where A is known as the *inter-atomic energy* and is related to the quality of the mesh (lower is better), and B is termed the *image energy* and is related to how close the atoms are to features of interest (lower values mean better placed atoms). In the Improved Mesh formulation, the atomic energy A is given by

$$A = \gamma \left(\frac{1}{2} \sum_{i=1}^{n} \sum_{j=i}^{n} \phi[\frac{|x_i - x_j|}{d(x_j)}] \right) + (1 - \gamma) \sum_{i=1}^{n} \frac{\mathcal{L}(x_i)}{d(x_i)} \tag{2}$$

where γ acts as a weighting factor between Hale's original distance-based inter-atomic energy and the Laplacian coordinate-based energy.

4. EXPERIMENTS

We have conducted two experiments using a synthetic seismic data set for a geological block. This data is a piece of the Overthrust Model (Aminzadeh et al., 1997).

The first experiment is based on Hale's approach, and the second on the Improved Atomic Meshes. The 3D dataset had 161x162x563 pixels, and the nominal distance employed was 15 pixels (generating around 9800 atoms).

The scale factor β was 0.5 in both experiments, which means an equal weight for the mesh quality and the feature alignment. The Improved Atomic Meshes method also applied the projection scheme with a threshold of 0.8, and the iterative optimization process used a random movement factor of 10% of the nominal atom separation distance.

The final mesh created by the Improved approach can be seen in Figure 5, and Figure 6 depicts a detail of this mesh when cut by two orthogonal planes, where the intersections with the tetrahedra were drawn on the planes.

It should be noted that it is possible to extract surfaces separating adjacent layers through a simple procedure. First, all tetrahedra with baricenters within a given threshold, between 0 and 255 (pixel values), are marked. Then, the surfaces belonging to one marked and one unmarked tetrahedra are output (see the example shown in Figure 7).

Figure 5: A cut of an atomic mesh obtained with the improved method.

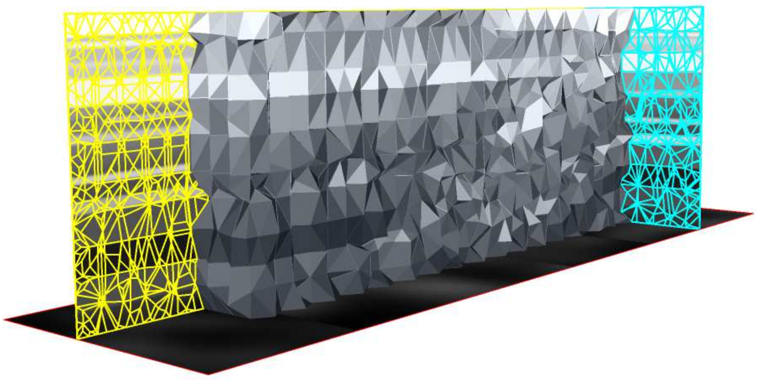

Figure 6: Cross-sections of the sample improved 3D mesh.

An histogram with the minimum dihedral angles of both methods is depicted in Figure 8. This histogram has been normalized, because Hale's approach generated a greater amount of tetrahedra than the Improved approach.

We have two strategies to evaluate the adequacy of the mesh to the 3D image. The first is a global strategy, which accumulates the difference, pixel by pixel, between the original image and an image created from the mesh (Figure 9). The second evaluates how close the edges and the pixels are. The rationale is that if an edge is on a feature, then the linear interpolation between its two vertex colors will produce similar pixels, when compared to the original image. Table 1 summarizes the results.

Table 1: Mesh Adequacy.

Method	Total Difference Average	Edge Difference Average
Hale	9.16	4.33
Improved	7.52	2.52

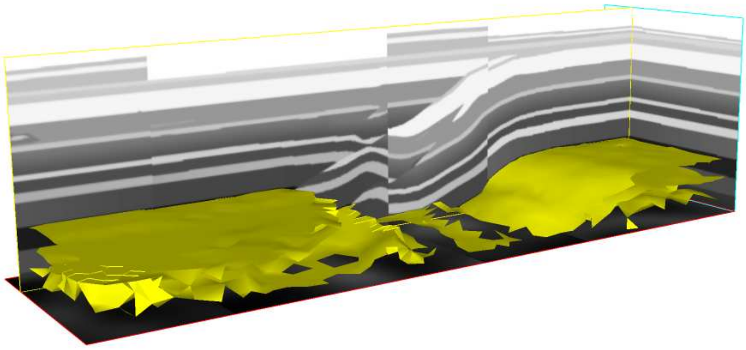

Figure 7: Example of surface composed of mesh triangles straddling a given threshold value.

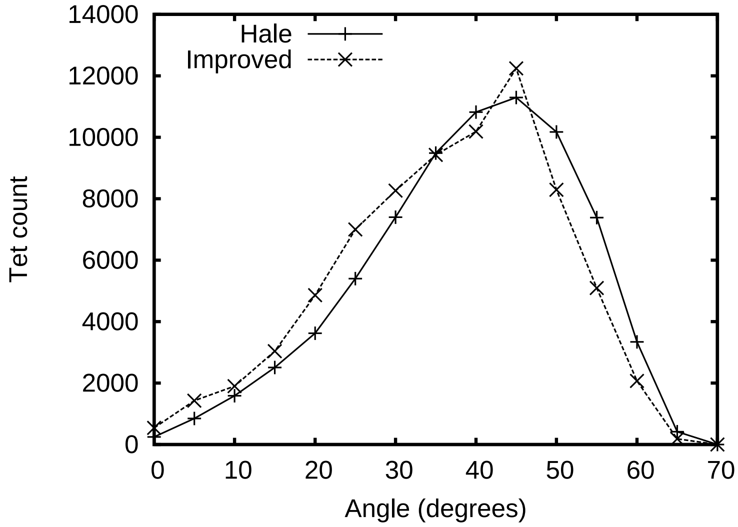

Figure 8: Histogram of Minimum Dihedral Angles.

5. CONCLUSIONS

We have extended to 3D, and implemented, the Improved Atomic Meshes approach, along with the 3D version of the original Atomic Meshes, for the sake of comparison. Our implementation is totally based on "open software", such as, CGAL (http://www.cgal.org), a computational geometry library, for generating the Delaunay Triangulation, the VTK toolkit (http://www.vtk.org), for visualizing the results, and Qt (http://trolltech.com) for the interface.

The enhancement of features is a fundamental step in the presented methodology, and other edge detecting filters should be carefully studied for this purpose. In practice, a seismic should be filtered many times prior to the analysis carried out by a geologist or geophysicist. It is expected that the set of faults and horizons compart the image into a set of regions, which are going to compose the geological layers. However, if the input image does not permit the obtaining of closed regions, maybe because it has not been filtered appropriately, the methodology will not be able to close the "holes".

Based on our experiments, we conclude that the quality of the mesh is worst in the Improved approach, mainly because the projection tends to produce more elongated tetrahedra. However, the Improved mesh adheres more closely to the features of the image.

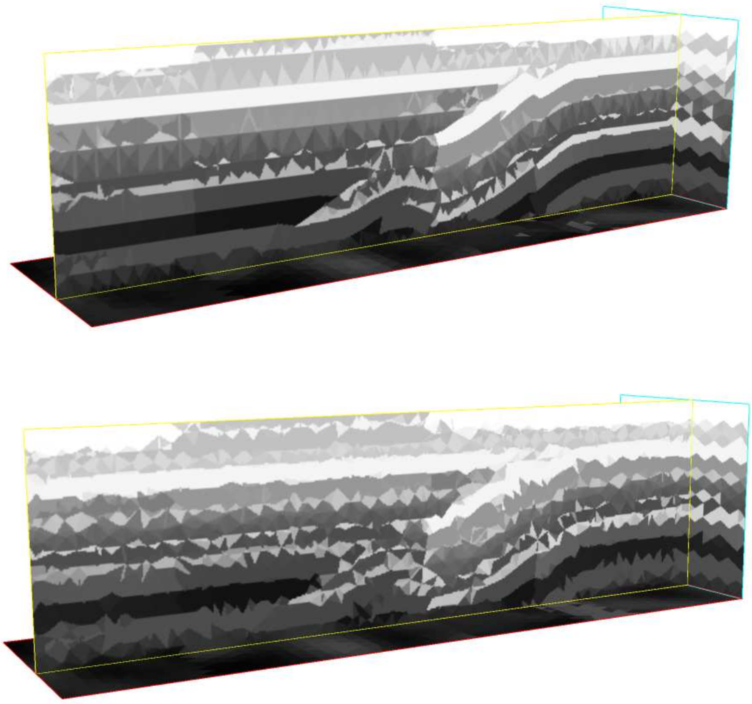

Figure 9: Images obtained for the mesh adequacy measurement: Improved method (top) and Hale's method (bottom).

It should be pointed out that the quality of the mesh could have been improved by several methods, such as edge flipping. It is notorious that a Delaunay triangulation, in 3D, produces, in general, a fair amount of degenerated tetrahedra, known as "slivers". Sliver tetrahedra must be always eliminated, because they pose numerical instabilities on any simulation carried out. However, we did not post-process the meshes in this work.

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