Hidden Object Reconstruction From Acoustic Slices

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Abstract

A method for reconstructing 3D models from cross-sectional seismic signals, which could be used in visualizing underground objects, is presented. The new algorithm starts with preprocessing the sonar images by thresholding, segmenting, contour finding, point sampling and then triangulating. The main objective of this algorithm was to produce the smoothest possible model for branching bodies taking into consideration that the slices might be far apart in reality and consequently a novel branching/ interpolation technique was used that proved superior to existing methods and at the same time did not need involvement of the user at any stage. Seismic simulations have been used to test the algorithm and we succeeded in reconstructing the tomb of Tut Ankh Amen (An Egyptian Pharaoh) from simulated slices. .

1. Introduction

Visualizing underground objects has many applications in geology and archaeology. For example, if an archaeologist is searching for an underground object in a certain piece of land then he/she will have to dig and see for himself. An easier way of doing that would be the use of seismic soundings and from the signals of these soundings, geophysicists will be able to know whether there is an underground object or not. An even better way is to visualize the underground object by reconstructing a 3D model of those objects from the sonar slices. The purpose of this paper is to explain a method for implementing such a solution. The process involves processing the sonar images and triangulating the points obtained from those images.

There is a wealth of previous work in the area of 3D reconstruction from slices. Most of this, such as [7] and [3], ignore the problem of having a branching body, in which a single contour in one slice corresponds to two or more contours in the next; others such as [1,2] explain how to deal with branching bodies, but their algorithms have several other limitations (mentioned in Section 4). Moreover, due to the unavailability of a large number of sources and receivers, the distances between source/ receiver lines might be large compared with the size of the object under investigation. To solve this problem an interpolation algorithm is used to generate a number of cross-sectional slices between the available slices, effectively smoothing the reconstructed model.

All the surveyed software packages for 3D reconstruction make the user select interactively the objects in the slices that must be taken into consideration in the 3D reconstruction; this is usually done by either allowing the user to select, with free hand, the desired objects, or selecting a threshold value which is adequate). Therefore, there is a need for an automatic system were the user should not be involved altogether or at least does not get involved for each model reconstruction (i.e. set some parameters for a class of images to be used as input to the reconstruction process).

Here, we start with a brief introduction to seismic data processing and to the different geometries of seismic surveys which are important for the visualization of how the planar seismic slices are obtained. In Section 3, the details of the preprocessing stage will be explained, and in Section 4 the novel technique for 3D reconstruction will be presented. Finally, in Section 5, the results of applying this algorithm to some synthetic and simulated seismic slices will be presented and compared to some existing algorithms and software packages.

2. Seismic signals

To produce a seismic signal a pair of seismic source and a geophone is needed. The source and the geophone (sometimes called receiver) are fixed on the surface of the earth and a sound wave (sometimes with a very high frequency) is emitted from the source. The wave travels through the earth until it reaches a subsurface (an interface between two media with two different velocities of sound) and gets reflected back to the surface of the earth. The receiver will then record the reflected signal. This process will produce a two direction time map for the receiver. In other words, a peak signal will appear after the time needed for the wave to go down and then up after reflection. The following paragraphs will explain the different geometries for sources and receivers and then the sequence of data

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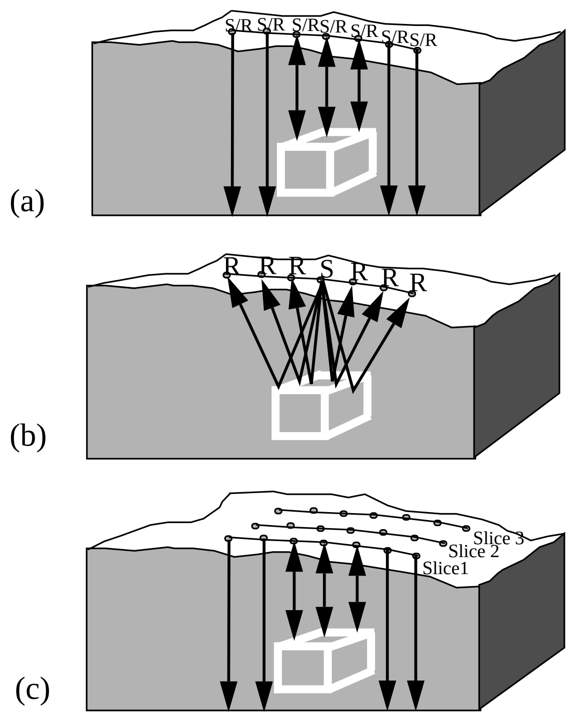


Figure 1. Phone geometry.

A zero offset arrangement. S/R means a source/ receiver pair.(b) A common source arrangement. (c) Parallel seismic lines with 3 lines of 7 S/R combinations.Each line becomes one slice in the 3D reconstruction

processing needed to produce a cross-sectional representation of the underground subsurfaces from the two direction time maps.

Different arrangements of sources and receivers are possible. The *zero offset* arrangement is shown in Figure 1a. In this arrangement, the sources and the receivers coincide; that is, they are virtually at the same point on the surface of the earth. This, of course, is not possible in practice and it is used only in simulations. The resulting signals are already stacked and they only need to be *migrated* (See also section 5) to produce the 2-D cross-section of the objects surveyed under the surface of the earth.

The second arrangement is the *common source* in which we have one source and a spread of equally spaced receivers over the area to be surveyed. An illustration of this arrangement is shown in Figure 1b. These two arrangements produce parallel planar cross-sections when the lines on sources and receivers are arranged in parallel over the surface of the earth as shown in Figure 1c. To produce a cross-sectional slice of underground objects from sonar signals a series of data processing operations should be performed. These operations are performed in the sequence: *deconvolution*, *stacking* and *migration*.

Deconvolution restores the original unblurred signal. The recorded seismogram (seismic map) could be modeled as a convolution between the earth's impulse response and the seismic wavelet. This wavelet is a combination of source signature, geophone response, recording filter...etc. What we want is the earth's impulse response representing the true reflections. So, the seismic wavelet is compressed to a spike so that the earth's impulse response is produced.

Next, stacking produces a zero-offset equivalent of the signals (the original arrangement might have been in a different geometry). Finally, the result of the migration process is a cross-sectional slice of the underground objects. The migration process is simply a mapping from the time values produced at each receiver to an image representing the underground subsurfaces. This could also be considered to be a mapping from the image produced by the arrangement in Figure 1c to an image which is equivalent to one obtained by a CCD.

3. Preprocessing

Input slices are images having 256 gray levels. The slices are parallel in 3D space and the Z parameter of each slice is input to the program. The main purpose of the preprocessing stage is to produce, for each contour in each slice, a series of points that represent those contours so that triangulation can be performed using the sample points in each contour for each two consecutive slices. Slices are first thresholded, then segmented, and finally sample points for each object in each slice are produced. The sampled points in each pair of slices are matched and the matched points are connected to form the 3D mesh which is then projected perspectively on the 2D plane. The process is described using an image from a CAT scan sequence of a human skull (Figure 2a).

Thresholding is the process of producing a binary image that contains black regions representing objects of interest in the original grey scale image. In most of the available 3D reconstruction software packages the user has to select a threshold value for each image (and sometimes it is more limited to one threshold value for all the slices). To automate this process a large set of the available thresholding algorithms were tested for the CT scan image and simulated seismic slices. The following is a list of all the thresholding algorithms tested:

- Thresholding using edge pixels.
- Iterative selection thresholding explained in [10,11].
- Method of grey level histograms.
- Entropy methods presented in [5,6,9]
- Fuzzy sets methods presented in [4] and [12].

- The mean method were 50% of the pixels in the finally thresholded image are black and the other 50% of the pixels is white.
- The *two-peaks* method were two peaks in the histogram of an image are located and a low point between those two peaks is selected to be the threshold value.

All of the above algorithms produce a different threshold for each slice. They are classified as single threshold algorithms, as opposed to regional threshold algorithms which require more processing time. Each of the produced images, for each of the above algorithms, was compared subjectively to an image where the user selected the threshold value himself. Also, a the whole preprocessing stage is completed for each of the above algorithms and then the produced 3D model was compared to a model produced by interactively selecting a threshold. The result of these subjective comparisons yielded the result that the entropy method for thresholding as described in [6] is the best when compared against the others, and could be used for automatically thresholding seismic slices; this was the method employed by our system.

Applying this algorithm to the image in Figure 2a, the output will be the bi-level image shown in Figure 2b. Notice how some noisy objects are produced from this process. This will be prevented in the hybrid algorithm described below.

Each thresholded slice is processed to produce a map which gives the locations of all the different objects in the slice. The segmentation procedure starts with scanning the image and stopping when a pixel value of 0 (an object) is encountered. This pixel location is passed to the marking function which marks (or labels) all the 8-neighbors of that pixel with a value other than 0 (object) and 255 (background). The marking function proceeds to mark all the neighboring pixels until no more neighboring unmarked pixels exist. The process is repeated for all the objects in the image slice. The final output is an image with 255 as background pixel values and a different pixel value for all the pixels in each object (Figure 2c). One algorithm to do this is explained in [8].

Next, for each object in the slice, its contour is found. Contours are found by scanning the whole image for values other than 255 (i.e. we are looking for object pixels) and if this pixel has a neighbor which is a background (255) then it is recorded as a contour pixel, otherwise it is not a contour pixel. When we look for neighboring background pixels, the algorithm examines the up, down, right and left pixels only so that the produced contour is 4-connected with the background.

Finally, the last step in the preprocessing stage generates the points that are going to be used in the triangulation process. Each contour is traced using a chain code method (E.G. [8]) and sample points are taken at constant steps. The sampling rate is constant for all the contours in all the slices. For example, if the sampling rate is 7, then the algorithm records a pixel every 7 pixels along the contour under investigation. These points are the definition of the contour in 3D space and at the end straight lines will be drown between these points for each contour. Figure 2e shows the result of applying the chain algorithm to the image of CT scan. Notice how the points are very close to each other when the sample step is 3 in that figure. Of course, using a sample step more than 3, say 10, will produce a coarser representation of the contour and consequently this will affect the quality (smoothness) of the produced triangular mesh since the number of line segments (triangle bases) will be fewer.

3.1 The reconstruction algorithm

The new algorithm for reconstruction from slices can now be described. The only technique that was borrowed from elsewhere is the Ganapathy triangulation method although the initial step in that algorithm was modified in our implementation to enhance the quality of the produced image.

Before triangulation takes place a contour mapping process is performed; this maps corresponding contours in each pair of consecutive slices. In this process the contours of each slice are compared to each other in terms of area and/or center of mass and/or convexity according to user choice. A similarity measure is calculated according to the following equation.

$$Similarity = \frac{a \bullet b}{(a \bullet a + b \bullet b - a \bullet b)}$$

Where **a** is the feature vector for the source contour and **b** is the feature vector for the destination contour [8]. Notice that the similarity measure ranges from 0 to 1. If the value of the similarity measure is above a certain threshold, say 0.8, the corresponding location in a boolean matrix is set and consequently the corresponding two contours will be connected. For example, if we have 4 contours in the source slice and 5 contours in the destination slice, the mapping matrix might look as the one shown below. A value of one at any location means that the two contours at this row and column are similar and they should be connected. Therefore, in this matrix, we have 4 situations:

[1] Source 1 is branching to Dest 1 and Dest 2

[2] Dest 3 is branching to Source 2 and Source 3.

[3] Source 4 is connected to Dest 4

[4] Dest 5 is the beginning of an object. (conversely, if any contour in the source slice is not related to any con-

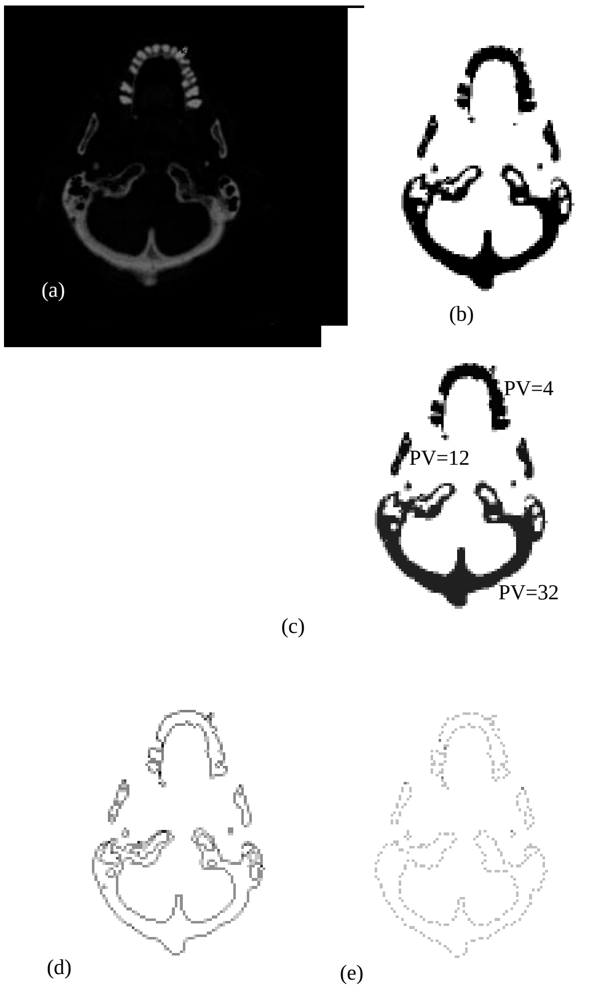


Figure 2. Steps in the pre-processing of a slice.

a) A CT Slice through the upper jaw and the lower part of the skull. (b) The same slice after thresholding. (c) Segmented into connected regions (PV = pixel value) (d) Contours of the segmented slice. (e) Sampled contours with a step size of 3..

tour in the destination slice, it would have been the end of an object).

When we find a 1 at any location in the contour mapping

	Source 1	Source 2	Source 3	Source 4
Dest 1	1	0	0	0
Dest 2	1	0	0	0
Dest 3	0	1	1	0
Dest 4	0	0	0	1
Dest 5	0	0	0	0

matrix we connect the corresponding contours. So, if contour x, in the source slice, is mapped to contours y and z, in the destination slice, then contour x is triangulated with contour y and then contour x is triangulated again with contour z. The produced triangles will overlap at the point of branching giving a more realistic representation.

Having a high similarity threshold will prevent different contours from being connected (i.e. the mapping matrix will have less 1's than required) and having a low one will allow more contours to be connected together yielding a more connected model (i.e. the mapping matrix will have more 1's than required). So, care should be taken while choosing a similarity threshold for a certain class of images.

Due to the fact that slices might be distant from each other, due to lack of a large number of sources and receivers, an interpolation algorithm was developed. This algorithm is executed whenever the distance between 2 slices is above a certain threshold. The interpolation threshold depends on the spacing of the source/receiver lines. If the spacing is large then the interpolation threshold should be small enough to account for the missing slices. On the other hand, if the spacing is smallcompared to the size of the object under investigation then we might not need to interpolate altogether. So in most cases it is advised that a small threshold value be used to enhance the quality of the reconstructed model. This threshold might be equivalent to 25 centimetres - 50 centimetres on the surface of the earth since the most common spacing between sources/receivers lines is 1 meter.

The interpolation process starts by choosing the same number of points on each of the contours and then the linear interpolation is performed to produce more slices between the 2 distant contours. The number of new slices is chosen to be

$$NewSlices = \frac{DistanceBetweenSlices}{InterpolationDistanceThreshold}$$

The finally produced figure is smoother than the one produced by just triangulating the two distant contours without interpolation. See results of the interpolation algorithm in Section 5 below.

The process of connecting the sampled points in two consecutive contours using triangles is called triangulation. Many methods were introduced in the literature and one of those methods is employed here namely the method described in [3]. In that paper the author mentioned that the best way to find the first two starting points (one on each contour) to start the triangulation with are the left most sampled points (points with minimum x-axis value) in each contour. This happened to be not accurate enough when the two contours to be triangulated are of totally different shapes. In this case the reconstructed shape looks twisted and the triangles happened to have a large surface area although we are looking for minimum surface area triangles since we should be connecting the closest points to each other. Thus, a new optimal technique was developed to account for this inaccuracy. A point X_0 is selected from the source contour and then Euclidean distance is measured from X_0 to Y_j another point in the destination contour. Then the distance between X_1 and Y_{j+1} is measured and added to the previously calculated distance and so on for all the points until we reach the end of one of the two contours. The process is repeated starting from another Y_j at the destination contour. The process keeps on going until we started from all the possible points on the destination contour. The Y_j which yields the minimum total line segment lengths is chosen to be the most correct point to start triangulation from with X_0. This process could be formulated by the formula:

$$Minimize\left(\sum_{j=r}^{n}\sum_{i=0}^{m} ED\,(X_i, Y_j)\right)\forall r$$

Where n and m are the numbers of points in the destination and source contours respectively, ED is the Euclidean Distance measure between 2 points in 3D and r is the initial point in the destination contour. The Y_r which gives the minimum of that formula is the one which should be used to be connected to X_0 and the process continues to connect all the other points using the Ganapthy method.

4. Results: Branching and interpolation

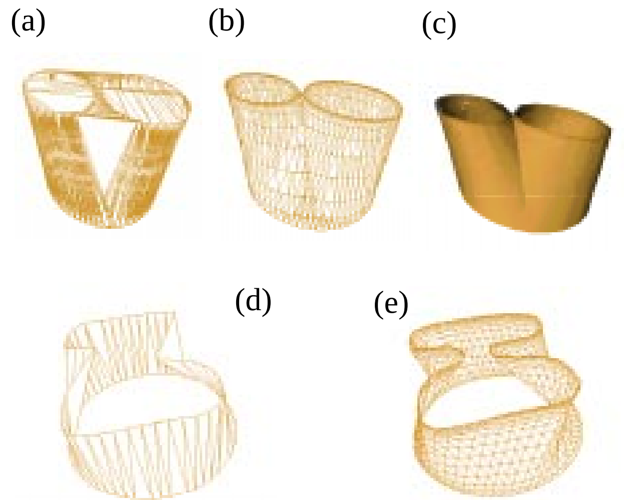
The method described in [2] for branching is not adequate when the contours have awkward shapes, as admitted by the authors. Thus, the presented algorithm here should be superior to at least this method. We also compared our method to a Delaunay triangulation method that takes into consideration branching cross-sections. The figure shown below (Figure 3a) is a reconstruction of a branching body. Notice that in this figure all the points were triangulated, even the ones at the same slice (level). This is considered one of the drawbacks of Delaunay triangulation. Another drawback is the assumption that the branching point is located at the lower slice which might not be true in reality.

The algorithm used to produce the reconstruction of Figure 3a is called Detri[1]. The Delaunay triangulations are not rendered, in order to make clear how the tetrahedrons appear. More examples of interpolating between two slices are shown in figures 3b-3e.

1. it has been developed by E.P.Muke at the Los Alamos National Laboratory in California

Figure 3. Results from reconstruction methods.

(a) Delaunay triangulation of a branching body. (b) The triangular mesh produced by the hybrid algorithm on a branching body. Interpolation is used to smooth the object. (c) The hybrid method used to reconstruct abranching model (one circle to two circles).(d) Triangulation between an irregular contour and a circular one. Without interpolation the model is not smooth and the shape of the contour is distorted. (e) Using interpolation, the model is smooth and the irregular shape



The following figures show the experiment done to reconstruct a 3D model from a simulated series of sonar slices of the tomb of Tut Ankh Amen. The first two figures (Figure 4a and 4c) show the actual shape of the tomb from a cross-sectional view and a top view. These two figures were used to produce the simulated slices using GX2.

Ten equally spaced slices have been modeled using GX2[2]. In each slice a cross-section taken horizontally in figure 15 is modelled using GX2. A zero offset simulation was used to produce ultrasound signals. The spacing of the Source / Receiver pairs were 25 centimetres. Thus, we have 101 S/R pair along the 20 meters line (see upper 3 images in Figure 5). In each of those images, the horizontal axis is the receiver number and the vertical axis is the two way time map (down to the reflecting surface and back to the surface of the earth) in seconds. The bright spots represent the reflections from the upper surface of the tomb and the dark spots represent the lower surface. Those signals were

2. GX2 is a software package used to simulate seismic soundings and the output of these simulations is the image of the received waves. GX2 is a registered trademark of GX Technologies Inc.

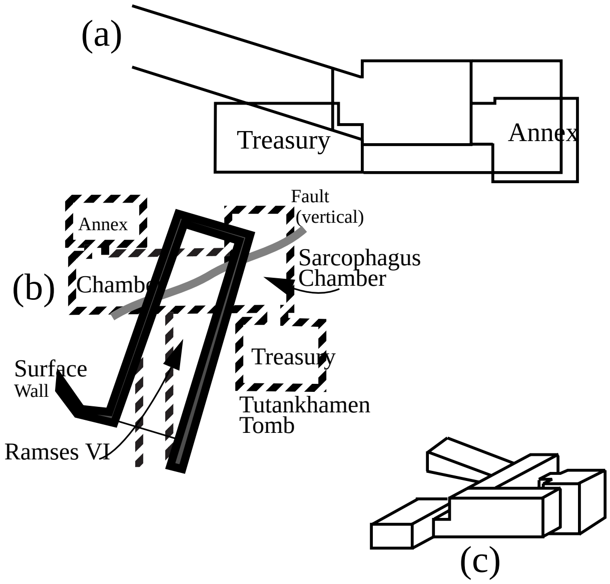


Figure 4. (a) Cross-sectional view ofthe tomb of Tut Ankh Amen.

(b) Top view of the tomb; the dashed lines are the tomb walls. (c)A rough 3D sketch.

exported to SU[1] where Kirchhoff migration was performed to produce equivalent cross-slices. The SU Kirchhoff depth migrated slices are shown in the lower 3 images of Figure 5. In each of those migrated images the horizontal axis is offset above the ground and the vertical axis in depth inside the earth. We are interested in the bright spots which are the reflections from the upper surface of the tomb.

The migrated images were used in the sequence shown (with slice number 6/7 being used twice) to reconstruct a 3D model for the tomb (Figure 6a). The time taken to produce this model was 32 seconds on an SGI machine (approximately 80% of this time was for preprocessing). The following parameter values were used for reprocessing and triangulating the above slices:

- Thresholding algorithm: Entropy method [6].
- Area threshold: 100 pixels (Regions in the segmentation process with an area of less than 100 pixels were discarded since they could be considered as noise).
- Interpolation method: linear.
- Features used to map contours: Center of mass only.
- Similarity threshold for mapping contours: 0.8
- Triangulation method: A variation of the Ganapthy method as described above in Section 4.3.

1. SU is a seismic data processing software package developed at the Colorado school of mines.

The above parameters will be constant for the class of images under investigation (namely clear sonar images) except for the interpolation threshold which depends on the relative relation between the spacing of the source/receiver lines and the size of the object to be surveyed as mentioned above in Section 4.2. Consequently, the user will not change any of the parameters unless a whole new class of seismic images (e.g. noisy) is used. Thus, the developed system is considered to be automatic compared to other software packages where the user has to enter a threshold value for the different slices.

The same slices of Tut's tomb were imported to 3DVIEWNIX[2] and the image shown in Figure 6b was produced in 270 seconds on an SGI machine excluding the time needed to select a threshold interactively (compared to the performance of our system this is approximately 9 times slower). Comparing the image produced in Figure 6a, the visual quality is the same where all the different compartments could be easily identified.

5. Conclusions

A new method for reconstructing 3D models from cross-sectional sonar images was presented. The presented algorithms proved to be superior to other tested algorithms in branching and interpolation yielding a smooth model at the end. Also, it is superior to other available software packages in terms of being automatic (user does not have to set parameters such as for thresholding) and fast. The

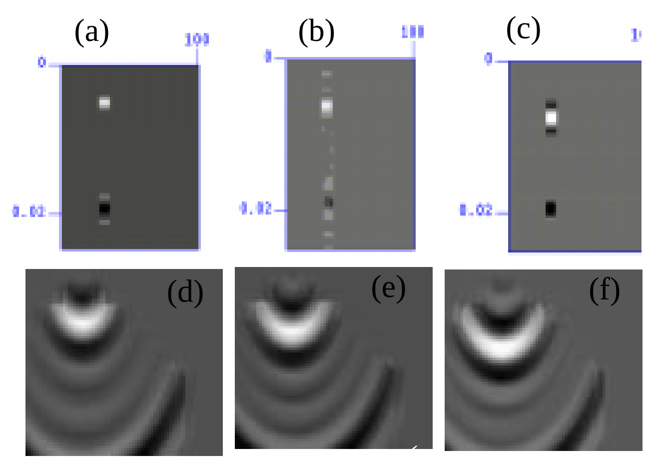


Figure 5. Migration.

(a-c) The first three slices before migration. (d-f) After migration.

2. A state of the art 3D reconstruction software package, for medical purposes, developed at the Radiology department in the University of Pennsylvania.

process involves preprocessing the images to find a series of contour points for the triangulation process and then a variation of the Ganapthy method is used to triangulate each pair of contours at a time. Contour mapping is performed to find similar contours on source and destination slices. The mapping could be 1:1 (no branching), m:1 (branching from destination to source) or 1:m (branching from source to destination). Each pair of matched contours is triangulated and the distance between each slice is taken into consideration such that whenever this distance is greater than a certain threshold a linear interpolation process between those two contours is performed to produce a smooth object.

Further research could be done in testing this algorithm with noisy data (or real data). Some changes to the preprocessing phase might take place in this case. For example, a smoothing of the produced sonar migrated images might yield good results. Another route for research might be to generalize the algorithm to the different geometries of seismic surveys such as the Vertical Seismic Profile (VSP).

6. References

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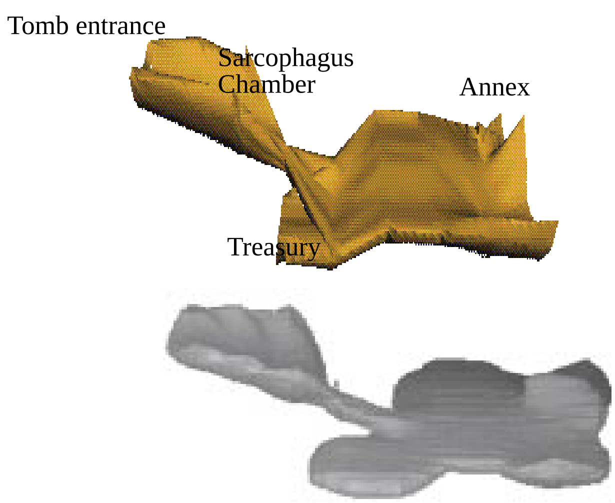

Figure 6. (a) A reconstruction of the tomb of Tut Ankh Amen.

Each of the different compartments could be easily identified. (b) Tut’s tomb produced by 3DVIEWUNIX.