Automated 3D Geological Surface Modelling With CDT

Zheng ZHONG, Yam Khoon TOR, and Xianhui ZHANG, Singapore

Key Words: 3D Geological Information System, Constrained Delaunay Triangulation, Transformation, DEM Simplification

SUMMARY

This paper presents a fast and efficient method to automate the generation of 3D geological surfaces from 2D geological polygons. The method was designed to meet our project requirement in creating a three-dimensional (3D) geologic map of Singapore.

Traditional geological maps which illustrate the distribution and orientation of geological structures and materials on a two-dimensional (2D) ground surface are no longer sufficient for the storing, displaying, and analysing of geological information. It is also difficult and expensive to update traditional maps that cover large areas.

Advances in computer technologies make it possible to create three-dimensional and interactive geological information systems. A Constrained Delaunay Triangulation (CDT) algorithm which considered the line segments of the geological polygons as constrained edges and all vertices of the digital elevation model (DEM) inside the polygons was applied to construct CDTs. Triangles outside the polygon were subsequently trimmed. To maintain an acceptable level of performance in setups consisting of typical graphics hardware, a Level of Details (LOD) algorithm using regular grids managed in a binary tree data structure was deployed.

This paper also presents 3DRock, a prototype 3D Geological Information System developed by the principal author to create a 3D geological model of Singapore.

Automated 3D Geological Surface Modelling With CDT

Zheng ZHONG, Yam Khoon TOR, and Xianhui ZHANG, Singapore

1. INTRODUCTION AND RELATED WORK

3D geological information systems provide a means to capture, model, manipulate, retrieve, analyse, and present geological situations. Tradition geological maps which illustrate the distribution and orientation of geological materials and structures on a 2D ground surfaces provide vast amounts of raw data. It is thus vital to develop a set of intelligent maps that shows features of geological formations and their relationships.

There are two approaches distinguished by different data schemes for modellng geological information. One approach is to scan a paper map, then drape or extrude it on a DEM as a thematic representation. This approach is a raster method. The second approach is to convert the geologic map into 3D vector objects of three basic kinds (points, lines, and areas) which can represent geological information as accurately as possible. The z value of the vertices can be interpolated on DEM or Triangulated Irregular Network (TIN) created from contour lines. The current commercial GIS softwares such as the ArcView® 3D Analyst™ extension[*] to ArcView GIS software can turn conventional 2D into 3D views. However these commercial softwares do not provide automated 3D geological surface modelling in combination with DEM to convert 2D to 3D geological objects. The method described in this paper provides automated generation of 3D geological surfaces from 2D geological polygons.

In recent times, there are three common methods used to manage real-time visualization of geospatial models. The more traditional method reduces geometric complexity by using appropriate LOD selection and management (Christopher Zach, 2002). In the second method, there exist a variety of image-based algorithms which improve rendering performance. The imposter-based approaches (Sillion, 1997) are very popular due to their simplicity and high performance. And lastly the third method is characterized by efficient occlusion-culling algorithms (Wonka, 1999; Wonka, 2001). These algorithms have been devised for special application areas for urban landscapes. In this study, we opted for performance gains by employing geometrical simplification algorithms for the DEMs.

2. DIGITAL ELEVATION MODEL OF SINGAPORE

DEM is a representation of the terrain surface by coordinates and numerical descriptions of altitude. DEM is easy to store and manipulate, and it gives a smoother, more natural appearance of derived terrain features. Therefore, the created DEM is the foundation of 3D geological maps when the z-coordinates of the vertices of geological formations can be

[*] http://www.esri.com/software/arcgis/extensions/3danalyst/index.html

interpolated. Thus, the first step is to create a grid DEM using the topographical maps of Singapore.

The data used consisted of 136 topographical map sheets, with 3D coordinates of roads, contour lines, and other information. The maps are in DXF format at a scale of 1:5000 (Figure 1). The scheme after Zhu et al. (1998) was adopted for building the DEM for Singapore. As building a DEM of coastal regions had one extra step than that of inland regions, the 136 topographic maps of Singapore were organized into 29 workspaces – 23 of them comprised coastal areas and the remaining 6 of inland areas. The contour lines, roads, and coastal lines were extracted for separate DEM generation using the CDT algorithm. These DEMs were then integrated into a whole DEM of Singapore using a DEM management Database. The final gridded DEM data with 5-metre intervals for Singapore was obtained (Figure 2). The file size is about 574MB.

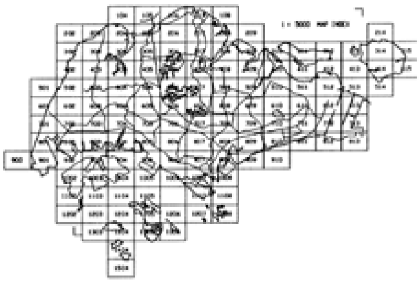


Figure 1. Map index of Singapore

Figure 2. Integrated DEM of Singapore

3. GEOLOGICAL SURFACES BUILT USING DELAUNAY TRIANGULATION

The interactive visualization of the geological models is of great importance for an in-depth analysis of the data set. 3D visualizations are readily created by rendering of the triangular facets. Therefore, the TIN method is a rational choice for building a more precise 3D geological formation. This section presents a new approach for establishing them through the integration of a DEM and such geological vector data. A CDT algorithm was applied to construct a triangulation scheme which considered the line segments of the geological polygons as constrained edges and all vertices of the DEM inside the polygons.

3.1 Introduction to CDT

The TIN model is a vector-based representation of a surface as a set of contiguous, non-overlapping triangles, made up of irregularly distributed nodes and lines with 3D coordinates (x, y, and z). Within each triangle, the surface is represented by a plane. The triangles are made from a set of points called mass points. Mass points can occur at any location, and if they are carefully selected, the more accurate the model of the surface will be. Mass points should be well placed at major changes in the shape of the surface e.g. peaks of mountains, floors of valleys, or the top and bottom edges of cliffs. Because mass points can be placed irregularly over a surface, TIN can have a higher resolution in areas where a surface is highly variable or where more details is desired and a lower resolution in areas that are less variable.

Deluanay triangulation (DT) is well known for its use in geometric design. DT has several advantages over other triangulation methods, and some of them are (1) The triangles are as equiangular as possible, thus reducing potential numerical precision problems created by long skinny triangles (2) the triangulation ensures that any point on the surface is as close as possible to a node, and (3) the triangulation is independent of the order in which the points are processed. The popularity of DT is two-fold. It yields "good shaped" triangles (in the plane) and the theory, mainly based on its dual (the Voronoi diagram), is well established. And significantly, the Delaunay swapping criteria are the only known criteria that can be used in Lawson's local optimization procedure (Lawson, 1977).

There are many DT constructing algorithms such as the incremental insertion (Lawson, 1977), divide and conquer, and triangulation growth (Green and Sibson, 1978). Among these, incremental insertion is most popular mainly because it is potentially dynamic, and it is simple to implement. The basic principle of constructing DT by incremental insertion is well known (Berg, 1997). It involves four main steps:

(1) Add four enclosing points that form a rectangle enclosing the data;
(2) Make two triangles out of those four points;
(3) Repeatedly add a point to the triangulation by:
  a. Finding the triangle the point lies in;
  b. Subdividing that triangle into three triangles; and
  c. Flipping the edges as necessary so that the new triangulation satisfies the Delaunay property.
(4) Identify the triangles containing one or more of the additional enclosing points and mark them as invisible so that what the user sees are only triangles containing the user data.

In the insertion algorithm, there are two most important operators: one is *point location* to find the triangle or component of the triangle in which the point lies, and another is *triangulation update* to restore the Deluanay property of the triangulation. *Point location* is dominated by an orientation (normally counterclockwise or CCW) test. *Triangulation update* mainly involves repeated use of in-circle tests and (assuming Lawson's algorithm is used) edge flips.

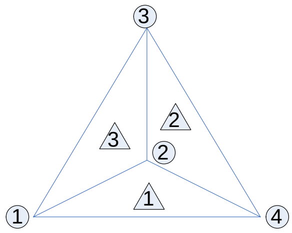
The TIN surfaces can be created in a way using vector features (include mass points, break lines, polygons, and many other features). CDT, a derived version of DT, accounts for constrained edges which are also referred to as pre-specified edges or break lines. Constrained edges may represent rivers, roads, lake boundaries and mountain ridges in cartography or linear features in CAD. They define and control surface behaviour in terms of smoothness and continuity. Therefore, they have a significant effect in terms of describing surface behaviour when incorporated in a surface model. CDT may also be used to construct triangulations with holes and triangulations with arbitrarily shaped (non-convex) boundaries while preserving Delaunay properties on the interior of the triangulation away from holes and boundaries. Its main steps are:

(1) Insert the constrained points using the same method described above;

(2) Find and remove any triangle edges that the constrained edge crosses creating a hole in the surface.
(3) Refill the hole with triangles making sure that the constrained edge is one of the new edges.

3.2 Triangle-based Data Structure

There are many possible topological structures or data structures for representing triangulations on computers. A data structure must be chosen in view of the needs and requirements in the actual application. When analyzing different data structures, one is always faced with a trade-off between storage requirements and efficiency of carrying out topological and geometric operations e.g. for visualization purposes one needs a data structure with fast access to data and sufficient topological information for traversing the topology fast when extracting sequences of triangles for the visualization system. This will normally require more storage than a data structure used only for storing a triangulation in a database.



Triangle #	Triangle i	j	k	neighbors $T_{j,k}$	$T_{k,i}$	$T_{i,j}$
1:	1	4	2	-	2	3
2:	2	4	3	1	-	3
3:	3	1	2	-	1	2

Figure 3. Data Structure for Deluanay Triangulation

TINs store GIS data for 3D surface models. A TIN model is composed of nodes, edges, triangles. Nodes are the fundamental building blocks of a TIN. The nodes originate from mass points and nodes of break lines contained in the source data. Every node is incorporated in the TIN triangulation. Each edge has two nodes, but a node may have two or more edges. So the basic unit is a triangle. Because a triangle consists of three lines connecting three nodes, each triangle will have three neighbors (except those on the side or periphery).

The data structure used to hold the triangulation is shown in Figure 3. Two lists of identical size: one triangle list with the indices of the vertices and a neighbor list with three references for each triangle to the adjacent triangles. The vertices for each triangle are listed anticlockwise and stored in a single column of a two-dimensional array V. Similarly, the list of adjacent triangles is held in the two-dimensional array T. The dash in the list denotes that the side lies on a boundary. And a triple (i, j, k) representing a triangle that spans i, j, and k has no unique starting point though the ordering of the vertices is counterclockwise. The fields in the columns i, j, and k would be represented as pointers to node objects or as integers representing node numbers. The adjacency information of each triangle $T_{i, j, k}$ is to record the three triangles sharing an edge with $T_{i, j, k}$. Each triple of triangles in a neighbor record is listed counterclockwise. $T_{j, k}$ is the neighbor triangle opposite vertex v_i in the triangle $T_{i,j,k}$, and correspondingly for $T_{k,i}$ and $T_{i,j}$. This data structure contains topological relationships. Given a triangle $T_{i,j,k}$ we know exactly what triangles are adjacent to it and where they are positioned relative to the vertices and the edges of $T_{i,j,k}$.

3.3 Building Geological Surfaces

There are two types of surface models: rasters and TINs. In contrast with topographical maps, DEM is stored in a raster format. They can be used as a base for detailed digital geological map (DGM). DGM includes sets of vector data such as geological formation, lakes, rivers, reservoirs, etc. All nodes of lines and polygons without z value in DGM can be interpolated on the DEM. The modeling procedure is complicated but very structured and systematic. In order to generate a 3D-surface geological map of Singapore, several conversion methods are available to take data from DGM to geological database. Interpolation and triangulation are the two main methods. Because of its simplicity and economy, TIN is used to build triangulated surfaces.

A geological surface is a continuous field of values that may vary over an infinite number of points e.g. points in an area on the earth's surface may vary in elevation. These vertices give more control over the shape of surface. A surface created from mass points alone reflects less well the actual terrain than a surface that is created from mass points and the boundaries of polygon. Each geological feature is formed by one or more polygons in a 2D digital map. And each polygon defines the area or boundaries (called hulls) of a geological object. The elevation of vertices inside the polygon can be interpolated from the created DEM.

Before triangulating 2D geological formation to 3D surfaces, the entire set of data points for the DEM and geological polygons firstly are first collected from source data. The vertices of DEM were regarded as mass points. In the same manner as rivers, roads, lake boundaries and mountain ridges are used for building a terrain surface, the boundaries of polygons had been also regarded as break lines in our study. They are integrated into the triangulation as closed sequences of three or more triangle edges. The areas outside the polygon and inside the interior polygons explicitly define the edge of the surface.

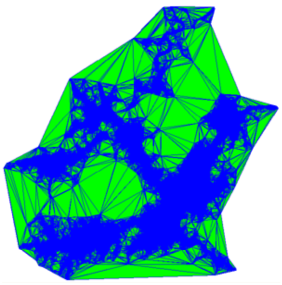


Figure 4. Constructed CDT

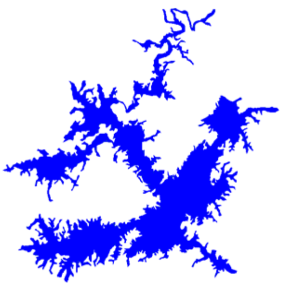


Figure 5. Trimmed triangles

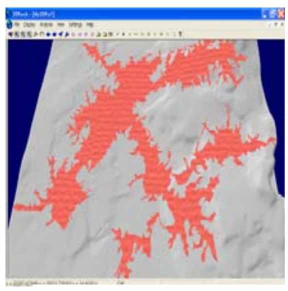


Figure 6. Draped surface on DEM

In order to trim invalid triangles, this paper extended data structure in Figure 3 to represent visibility by adding another one-dimensional array I. A visible triangle can be displayed and regarded as an element of a 3D surface. When visualizing, these invisible triangles do not display. However, they are still stored in the database as topological consistency for analysis needs to be maintained. Two exclusion features called Clip and Erase are defined to prevent the generation of erroneous information in regions outside the actual dataset. The Clip feature renders triangles that fall outside the polygons invisible; the Erase feature renders triangles that fall inside the polygons invisible. The steps of surface conversion include:

– Pre-process the targeted polygon and search all vertices of the DEM and polygons inside it.
– Interpolate all nodes without elevation on the DEM.
– Construct CDT as shown in Figure 4.
– Clip all triangles outside the polygon and erase all triangles inside interior polygons if they exist as shown in Figure 5, and
– Map the texture/material of the resulting surfaces as shown in Figure 6.

4. DEM SIMPLICATION

The DEM with 5m grid cells for Singapore (which had been automatically generated automatically from 1:5000 dxf files) was used as a datum for controlling the shape of surface. The 3D surfaces based on the size of a densely sampled DEM data can easily exceed the capabilities of a typical graphics hardware setup; and thus, surfaces based on densely sampled data makes interactive application inefficient. In our study, the LOD algorithm based on a binary tree structure was deployed to reduce the number of grid vertices of a DEM. TINs generated after simplifying grid-based DEMs are a good compromise between the simplicity of non-hierarchical grids and the good adaptability of TINs.

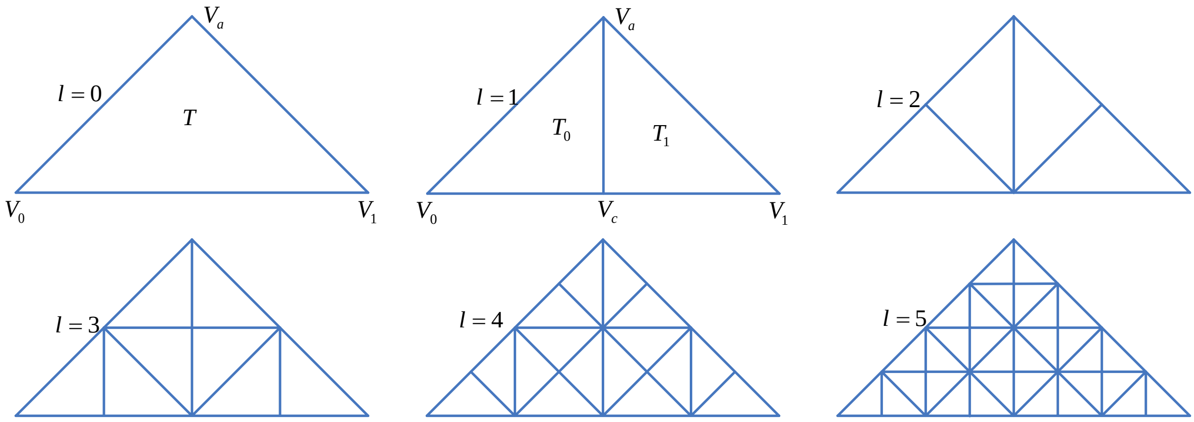


Figure 7. Levels 0-5 of a Binary Tree (Mark et al., 1997)

Binary triangulations is an efficient and elegant data structure for representing a special type of triangulation that can be considered as the result of recursive splitting of one triangle into two new triangles. Furthermore, binary triangulations are more flexible than quadtrees since they use twice the number of grid levels. Figure 7 shows the first few levels of a binary tree. The root triangle, $T = (V_a, V_0, V_1)$, is defined to be a right-isosceles triangle at the coarsest level of subdivision, $l = 0$. At the next-finer level ($l = 1$), the children of the root are defined by splitting the root along an edge formed from its apex vertex V_a to the midpoint V_c of its base edge (V_0, V_1). The left child of T is $T_0 = (V_c, V_a, V_0)$, while the right child of T is $T_1 = (V_c, V_1, V_a)$. The rest of the binary tree is defined by recursively repeating this splitting process.

T_B (Figure 8) is defined to be the base neighbour of T sharing base edge (V_0, V_1), T_L to be the left neighbour of T sharing left edge (V_a, V_0), and T_R to be the right neighbour of T sharing right edge (V_1, V_a).

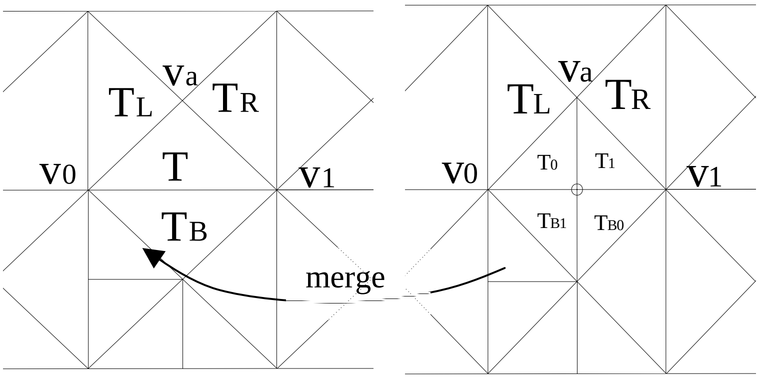
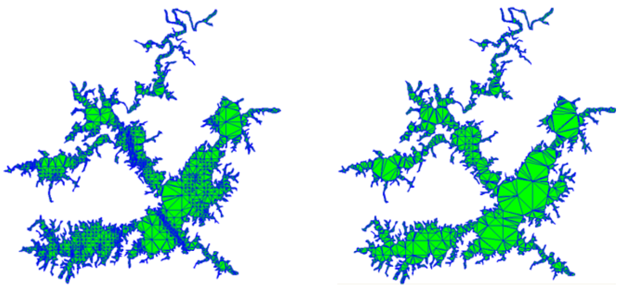


Figure 8. Merge Operation on a Binary Triangulation (Mark et al., 1997)

Figure 8 also shows merge operation on a binary triangulation. When T and T_B are both from the same level *l*, we refer to the pair (T, T_B) as a diamond. Merging can be applied to diamond (T, T_B) when the children of T and T_B (if T_B exists) are all in the triangulation. Merging triangles causes fewer triangles in the area and thus the triangulation of this area is simplified. The vertices constituting the boundary of a DEM will not be deleted because the parent of the triangles formed by them do not have base neighbour.



(a) 0.5 metre resolution (b) 2.5 metre resolution

Figure 9. Resulting CDTs after DEM simplification

The DEM-simplification algorithm in this study uses regular grids managed in a binary tree data structure, and it divides a large terrain into smaller blocks. We chose a polygon with

6030 line segments with origin resolution (0.0), 0.5, 1.0, 1.5, 2.0, 2.5 metre to simplify DEM. Table 1 illustrates the effect on processing time with respective to the resolution, the number of DEM vertices and the number of triangles. Figures 5 and 9 illustrate the resulting CDTs after DEM simplification at 0.0, 0.5, and 2.5 metre resolutions.

Table 1 Processing times with varying resolutions for LOD simplification

Resolution	Point	Triangle	Time(s)
0.0	90000	46192	97.26
0.5	10041	9977	15.64
1.0	4529	7523	11.09
1.5	2880	6742	9.313
2.0	2199	6479	8.172
2.5	1879	6337	7.844

5. 3DROCK

3DRock is the prototype 3D Geological Information System developed by the principal author to build 3D geological models of Singapore. It facilitates users to view and query the 3D models of the geological surfaces in a seamless manner. Figure 10 shows the display of the 3D geological map of Singapore in 3DRock. The blue surfaces on the DEM are reservoirs; the green lines represent expressways; and the red lines represent the roads. The other colours denote the distribution of geologic formations.

.

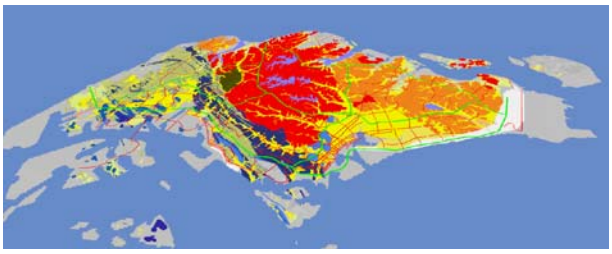


Figure 10. 3D geological map of Singapore

6 CONCLUSION AND RECOMMENDATION

Some key processes for automated 3D geological surface modelling such as data transformation and DEM simplification have been briefly presented. Other issues such as the processes of conversion and attachment of object attributes are required to be resolved.

REFERENCES

Christopher Zach, 2002, Integration of Geomorphing into Level of Detail Management for Real-time Rendering, Technical Report, VRVis Research Center, University of Graz.

F. Sillion, G. Drettakis, and B. Bodelet. 1997, Efficient Impostor Manipulation for Real-Time Visualization of Urban Scenery, Computer Graphics Forum (Proc. Of Eurographics' 97), Vol. 16(3), pp: 207-218

Green, P. J. and Sibson, R., 1978, Computing Dirichlet tessellations in the plane, The Computer Journal, Vol.21, pp. 168.

Lawson, C. L., 1977, Software for C^1 interpolation, Mathematical Software Ш, Academic Press, New York, pp. 161-194.

Sibson, R. 1978, Locally equiangular triangulations, The Computer Journal, Vol.21, pp. 243

Mark Duchaineau, MurrayWolinsky, David E. Sigeti, Mark C. Miller, Charles Aldrich, Mark B. Mineev-Weinstein, 1997, ROAMing Terrain: Real-time Optimally Adapting Meshes, IEEE Visualization '97 Proceedings, Phoenix AZ, pp: 19 –24

M. de Berg, M. van Kreveld, M. Overmars, O. Schwarzkopf, 1997, Algorithms and Applications, Computational Geometry, Springer-Verlag, Berlin.

Peter Wonka and Dieter Schmalstieg, 1999, Occluder Shadows for Fast Walkthroughs of Urban Environments. In Proc. Eurographics' 99, pp.51-60.

Peter Wonka. and Wimmer, M. and Sillion, F., 2001, Instant Visibility., In Proc. Eurographics' 01, pp.411-421.

Zhu Qing, Li Zhilin, Gong Jianya, Sui Haigang, 1998, The Scheme For The Database Building And Updating of 1:10000, ISPRS Commission IV Symposium on GIS – Between Visions and Applications, Vol. 32/4, pp: 473-478, Stuttgart, Germany

BIOGRAPHICAL NOTES

Academic experience: BEng, Wuhan Technical University of Surveying and Mapping MSc, Wuhan University PhD, Wuhan University
Professional experience: Research Fellow, Nanyang Technological University

CONTACT

Zhong Zheng
Protective Technology Research Centre
School of Civil & Environmental Engineering,
Nanyang Technological University
Singapore, 639798
Tel. 65-6790 5346
Email: zhongzheng@ntu.edu.sg
http://www.ntu.edu.sg/cee/staff/infrastructure/research/zhongzheng.asp