

# INTEGRATION OF TERRAIN MODELS AND BUILT-UP STRUCTURES USING CAD-TYPE EULER OPERATORS

Rebecca, O.C. Tse and Christopher Gold

Department of Land Surveying and Geo-Informatics

Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR

Tel: (852) 2766-5955; Fax: (852) 2330-2994

[Rebecca.Tse@polyu.edu.hk](mailto:Rebecca.Tse@polyu.edu.hk), [christophergold@voronoi.com](mailto:christophergold@voronoi.com)

Commission V, WG V/6

**KEY WORDS:** Triangular Irregular Network (TIN) models, Euler Operators, Quad-Edges, Computer-Aided Design (CAD)

## ABSTRACT:

Until recently terrain models were developed in a GIS, and built-up structures were modelled using a CAD system. Extending the current “2.5D” TIN model by incorporating CAD functions is a necessary development, while preserving topological integrity. A solid-modelling CAD system may be excessive for our “extended 2D” mapping needs, but the CAD “boundary representation” (b-rep) design, based on manifold models, addresses these problems well. TIN models of the terrain surface are well known in GIS, but are unable to represent cliffs, caves or holes, which are required to represent complex buildings. However, translating simple TIN operations into formal Euler Operators on a b-rep structure allow us to add simple CAD functionality by extending the number of Euler Operators, while guaranteeing the connectivity required for terrain modelling. Thus we may start with a TIN model and extrude buildings, bridges, etc. with operators that modify a specified number of faces, edges, vertices and holes, allowing the construction of a seamless representation of the single exterior surface of all land and building features.

## 1. INTRODUCTION

Within the world of GIS the TIN has been well known for more than 20 years. It is one of the basic models for representing digital terrain. A piece of land on the earth’s surface can be modelled as a terrain (Gold, 1979; Peucker et al, 1978). Applications of TINs to problems of runoff, etc., have also been well studied in the computational geometry literature (Weiler, 1986). The difficulties with this “2.5D” model are also well known, in particular the fact that the structure itself is only two-dimensional, the third dimension being only an attribute. This limitation contrasts strongly with the situation in the CAD world, as well as in 3D graphics, where surface meshes of complex 3D objects (plausible and implausible) are routinely generated. What is the big problem?

It is fairly clear that GIS is still firmly two-dimensional in its implementation, despite various attempts to extend it, and despite frequent complaints about the inability to model non-planar networks, bridges, caves, etc. within the traditional TIN surface model. This paper attempts to alleviate this problem somewhat, by moving gently towards an extended view of the traditional TIN. The first step is to recognise that a terrain surface modelled by a TIN is not a two-dimensional entity – it is an air- (or water-) earth interface, the boundary between the “Polyhedral Earth” and the exterior. Simply put: every TIN has an “underneath”. This causes few difficulties in practice.

Once this polyhedral model is accepted, attention naturally turns to other disciplines’ experience in polyhedral modelling. Computational geometry has developed a variety of tools for managing surface models (van Kreveld, 1997). In particular, we have been interested in the Quad-Edge structure (Gold, 1998; Guibas and Stolfi, 1985). Computer graphics workers have developed many tools used extensively today. In particular, the field of CAD has been developing tools for solid

model representation for many years, for example Baumgart in 1972 and Mantyla in 1981 and 1988.

In our current work we are using the CAD-type b-rep structure and Euler Operators to create a connected TIN model with holes (bridges or tunnels). Starting with the well-known TIN model, we have built a set of CAD-type Euler Operators, including the ability to form holes, which are easy to implement with the Quad-Edge structure. Secondly we show that all basic TIN modification operations may be performed with Euler Operators. Thirdly, we show that additional Euler Operators may be used to modify the surface form in various ways, including the insertion and deletion of holes that give the basic forms of bridges and tunnels.

Thus our work consists of four stages:

- Definitions of three levels of operators to achieve our desired system;
- The use of Quad-Edge structures to implement CAD-type Euler Operators;
- The use of Euler Operators to implement basic triangulation functions;
- The extension of our triangulation models with additional Euler Operators.

## 2. TINS AND CAD

The examination of CAD modelling techniques does not seem attractive at first sight. The intersection of cubes and tubes, as in Constructive Solid Geometry (CSG) modelling, hardly applies to terrain models. Modern non-manifold models of surfaces can have astoundingly complex data structures (Lee, 1999), and would be massive overkill for TIN enhancement. However, the simpler manifold-based “b-rep” CAD models appear to be feasible for our purposes. In particular, the careful specification of “Euler-Operators” that guarantee to preserve

the topological validity of the bounding surface seems particularly appropriate. Euler Operators ensure the integrity of boundary models. As stated by Mantyla in 1988, "In a "b-rep" model, an object is represented indirectly by a description of its boundary. The boundary is divided into a finite set of faces, which in turn are represented by their bounding edges and vertices." According to his definition, b-reps are best suited for objects bounded by a compact (i.e. bounded and closed) manifold. However, if the main concern were building a non-manifold object, it would be better to use other models.

In 1988 Weiler proposed non-manifold operators to manipulate topological data in non-manifold models. Moreover, they were not based on the basic Euler-Poincare formula, although some of the topological relationships still can be generalised by a new formula by (Masuda et al, 1990), although it is more complicated. Nevertheless, it may be valuable to extend the b-rep with Euler Operators into a non-manifold GIS model in the future. We conclude that to extend the TIN, the b-rep model is the most appropriate at present.

### 3. SIMPLICITY OF IMPLEMENTATION – THE QUAD-EDGE STRUCTURE

We have examined the basis for various sets of Euler operators mentioned in the CAD literature, and their data structures. This is usually the "Winged-Edge" data structure (Baumgart, 1972), which has a variety of supporting pointer structures, some of which, upon closer examination, are not necessary in order to maintain a TIN or triangulation-based b-rep surface model. In particular, if all faces are triangles, then no holes may be created in the interior of individual faces and thus some elements of both the Winged-Edge structure and the classical Euler Operators may be removed. We have used the Quad-Edge structure of (Guibas and Stolfi 1985). More particularly, the Quad-Edge structure has been used to implement a set of Euler Operators that have been shown to suffice for the maintenance of surface triangulations. According to (Weiler, 1986), if a topological representation contains enough information to recreate nine adjacency relationships without error or ambiguity, it can be considered a sufficient adjacency topology representation. These Euler Operators form the basis of the standard (two-dimensional) incremental triangulation algorithm. In addition, Euler Operators can serve to generate holes within our surfaces, thus permitting the modelling of bridges, overpasses etc. that are so conspicuously lacking in the traditional GIS TIN model. The individual Quad-Edge and Euler Operators take only a few lines of code each. "Make-Edge" and "Splice" (Figs. 1 & 2) are the two simple operations on the Quad-Edge structure, which is formed from four connected "Quad" objects, using the simple implementation of (Gold, 1998). Every Quad has three pointers:

- N – link to next Quad ("Next") anticlockwise around a face or vertex
- R – link to next ¼ Edge ("Rot") anticlockwise around the four Quads
- V – link to vertex (or face)

The Make Edge operator creates a new independent edge. The Splice operation, which is its own inverse, either splits a face loop and merges two vertex loops (upper to lower parts of Fig. 2) or else splits a vertex loop and merges two face loops (lower to upper). This operation suffices to maintain any connected graph on an orientable manifold, as is the case for CAD b-rep models, and TINs.

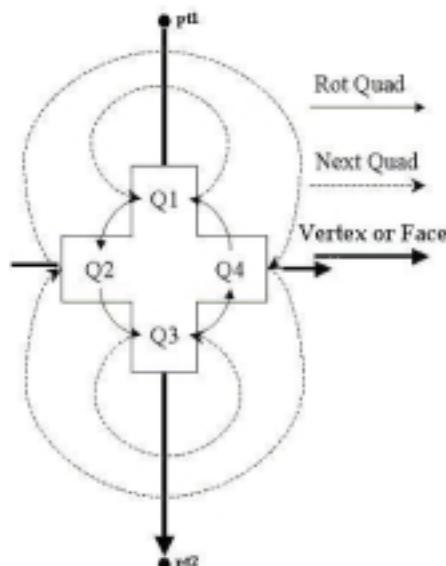


Figure 1. Make-Edge

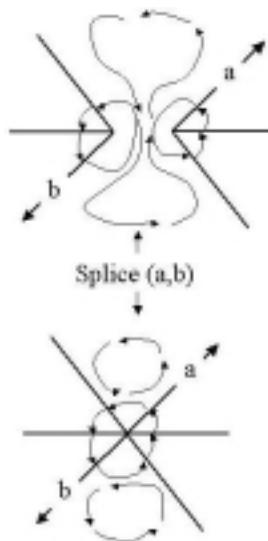


Figure 2. Splice

### 4. SELECTION OF A SET OF EULER OPERATORS

According to (Braid et al, 1978), five spanning Euler Operators (plus the Euler-Poincare formula) suffice to specify the number of elements in any b-rep model. Conversely, the inverse formulation serves to identify the number of Euler Operators needed to build a specified model, and to validate its topological integrity. The six elements of the solid model are: vertices; edges; faces; loops (or rings); holes; and bodies (or shells), and are usually based on the Winged-Edge structure.

However, in TINs there are no loops (holes in individual faces), so these will not be considered, leaving five elements. Thus four spanning Euler Operators suffice for TINs with holes. In the traditional TIN models there are no holes, so three Euler Operators will serve for our initial model, to be extended to four in section 7.

## 5. IMPLEMENTATION OF EULER OPERATORS USING QUAD-EDGE STRUCTURES

The three initial Euler Operators are described below. “Make Edge Vertex Vertex Face Shell” (MEVVFS) creates the initial shell, and “Kill Edge Vertex Vertex Face Shell” (KEVVFS) removes it. “Make Edge Face” (MEF) and its inverse “Kill Edge Face” (KEF) create or kill an edge and a face. “Split Edge Make Vertex” (SEMV) splits an edge, and its inverse is “Join Edge Kill Vertex” (JEKV). While other operators are possible, this set of operators is appropriate for a triangulation model, where no “dangling edges” are permitted.

### 5.1 MEVVS $\Leftrightarrow$ KEVFS

“MEVVFS” adds an edge, two vertices, one face and one shell to an empty model. Its inverse “KEVVFS” removes them. One Quad-Edge Operator is used to implement “MEVVFS” (which is simply “Make-Edge”) to create a single edge. In our approach the “Loop” (Mantyla, 1981; 1988; Zeid, 1991) around the single edge is really the back face of our model, so we consider this to be a face.

### 5.2 MEF $\Leftrightarrow$ KEF

“MEF” and “KEF” are used to create an edge and a face, and to delete them. In “MEF” we need to give two quads as parameters to make a new face. In “KEF” we need to give an edge as a parameter for removing the edge, and one face will be destroyed as this edge is removed. Fig. 3 shows the operation of “MEF” and “KEF”. “MEF” inputs two quads “a” and “b”, output is one new quad “e”. “KEF” removes an edge “e” using two splices and one face is killed.

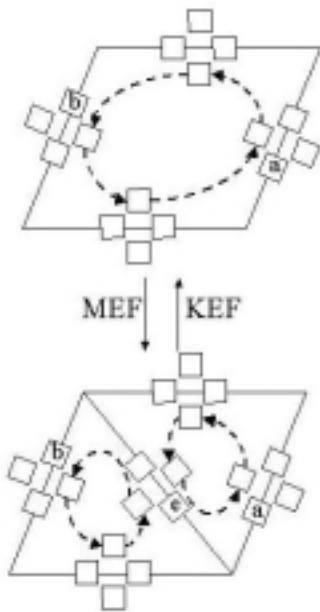


Figure 3. “MEF”  $\Leftrightarrow$  “KEF”

### 5.1. SEMV $\Leftrightarrow$ JEVK

We use “SEMV” and “JEKV” to split one edge into two pieces. This procedure adds or removes a point on an edge. It is useful for creating triangles without creating a dangling arc.

Fig. 4 shows the operators of “SEMV” and “JEKV”. “SEMV” splits edge “e” into two parts, and two parts are joined by “JEKV”, using splice operations.

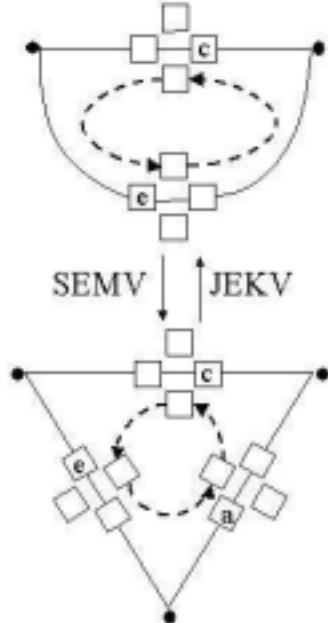


Figure 4. “SEMV”  $\Leftrightarrow$  “JEVK”

## 6. IMPLEMENTATION OF THE TIN MODEL USING EULER OPERATORS

In the TIN model we have three main functions, which are: create a first triangle; insert a point; and swap an edge. We use Euler Operators to implement triangulation functions. We use the functions “Big Triangle”, “Insert Point” and “Swap”. These also have inverses.

### 6.1 Big Triangle

In our model we limit ourselves to complete faces with no “dangling edges”, so we begin from nothing, and create the first triangle using “Big Triangle”. We kill the big triangle and go back to nothing by using the inverse functions as shown in Fig. 5. In creating the “Big Triangle”, three points are needed as input. Three different Euler Operators are used: “MEVVFS”, “MEF” and “SEMV”. 3 points (pt1, pt2, and pt3) are input to create the Big Triangle and 3 edges (e1, e2, and e3) are the output. “MEVVFS” creates the first edge “e1”. “MEF” creates a new edge “e3”. “SEMV” splits edge “e3”. To kill the Big Triangle, “JEKV” joins edge “e2” and “e3”. “KEF” kills edge “e3” and a face. “KEVVFS” kills the last edge “e1”, giving an empty space.

### 6.2 Insert Point

“Insert point” is another procedure that we use. In the TIN model the whole surface is formed by triangles, therefore we will insert a new point into an existing triangle. We can use “MEF”, “SEMV” and “MEF” to insert the new point, and “KEF”, “JEKV” and “KEF” to delete the point. Fig. 6 shows the procedure of inserting a new point. Inserting a new point makes three edges and two faces. “MEF” creates an edge “N4”. “SEMV” splits an edge “N4”. Last step “MEF” creates a new edge “N6”.

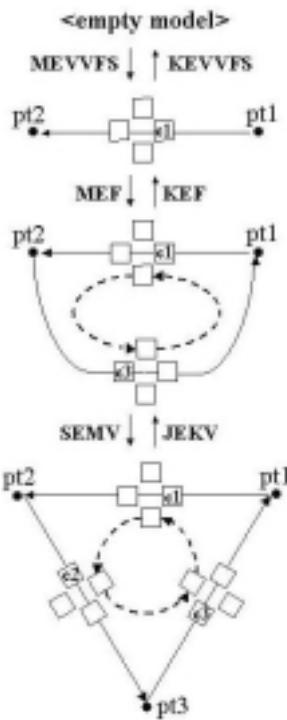


Figure 5. "Big Triangle"

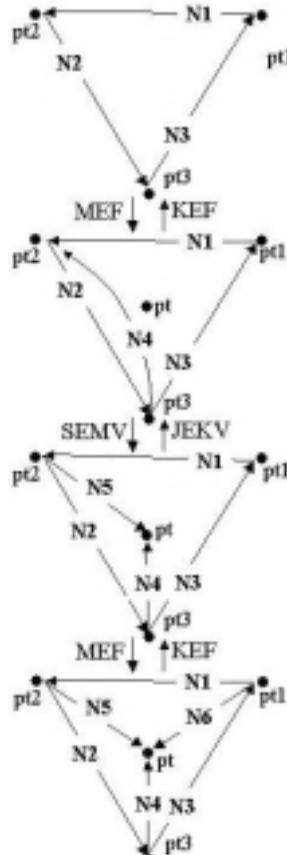


Figure 6. "Insert Point"

### 6.3 Swap

Swap is a procedure for swapping two edges inside the TIN model. For the Delaunay Triangulation, we use the "in-circle" test to test the triangle, and use the swap operator to change edges. The Delaunay Triangulation is based on the empty circum-circle criterion (Guibas and Stolfi, 1985). It has been accepted that the Delaunay Triangulation is the best criterion to use for triangle definition in many applications. Fig. 7 shows the steps for Swap using Euler Operators. We need to input an edge "e" to be changed. "KEF" kills the edge and "MEF" creates the edge. It swaps the edge in a quadrilateral.

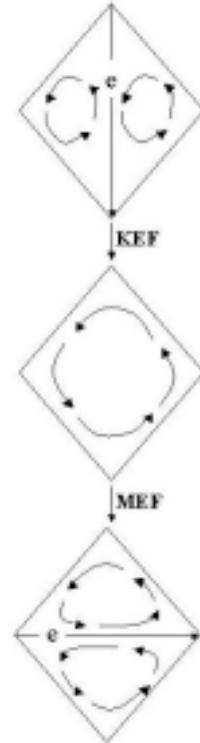


Figure 7. "Swap"

## 7. EXTENDING THE TIN MODEL USING EULER OPERATORS

So far we have merely re-formulated the traditional incremental algorithm, but with this background we can use Euler Operators to modify the TIN surface in other ways, e.g. by the insertion and deletion of holes. The operator "Make Edge Hole Kill Face" (MEHKF) consists of exactly the same code as "MEF" (Tse and Gold, 2001). However, instead of taking two Quad-Edges that are part of the same face loops as parameters, it takes Quad-Edges that are parts of separate face loops. The two triangles concerned are deleted, an edge is formed between the two triangles, and a new face is formed that loops through each of the deleted triangles and both sides of the new edge.

We select two triangles in an existing TIN model: their edges are ordered anti-clockwise from outside. Two original triangles from the TIN model are shown, looking from "inside" in Figs. 8-10. The order of the three edges inside the two triangles is 1 => 2 => 3 => 1 and 4 => 5 => 6 => 4. We make a new edge

between these two triangles and a hole is created. One face loop is created inside the hole and two triangle faces are killed. Fig. 8 shows the result of the first step "MEHKF". The connection of the edges will be

-  $1 \Rightarrow P \Rightarrow 5 \Rightarrow 6 \Rightarrow 4 \Rightarrow Q \Rightarrow 2 \Rightarrow 3 \Rightarrow 1$

Fig. 9 shows the result after performing "MEF". One new face is made and the connectivity of the edges will be

-  $1 \Rightarrow P \Rightarrow 5 \Rightarrow R \Rightarrow 1$  (New face) and

-  $3 \Rightarrow S \Rightarrow 6 \Rightarrow 4 \Rightarrow Q \Rightarrow 2 \Rightarrow 3$

Fig. 10 shows the result of the final "MEF". One new edge and face are created. The edges of the top face are running in clockwise order because of looking from outside. There are now three faces inside the hole, but the connectivity is preserved and you can navigate through the hole. Three more "MEF"s are used to split the faces inside the hole into triangles. We have therefore shown that the elementary Quad-Edge based Euler Operators are able to generate and modify the traditional TIN structure, permitting basic CAD operations.

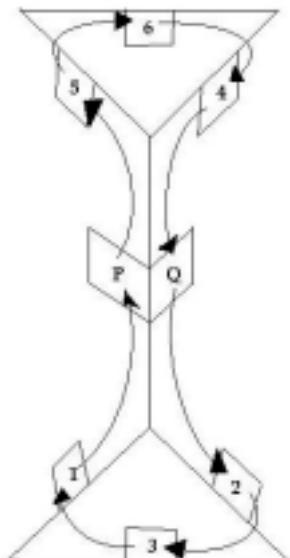


Figure 8. "MEHKF"

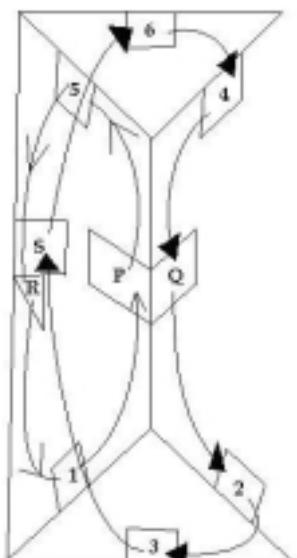


Figure 9. "MEF"

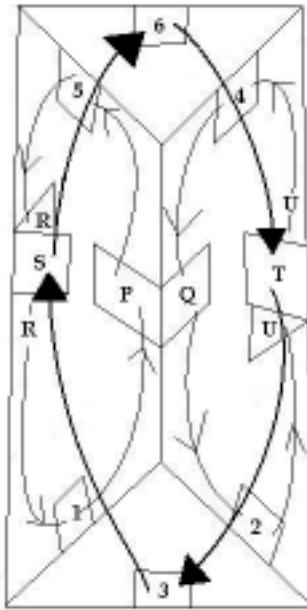


Figure 10. Third "MEF"

## 8. EXTENDED TINS WITH HOLES, BRIDGES OR BUILDINGS

With these basic operations we may build holes, bridges and buildings. Fig. 11 shows the side view of a TIN model. Fig. 12 shows a hole on the TIN generated with the method of section 7. We can use "swap" to enlarge the hole on the TIN model by swapping diagonals at the edge of the holes. Fig. 13 shows the enlarged hole.

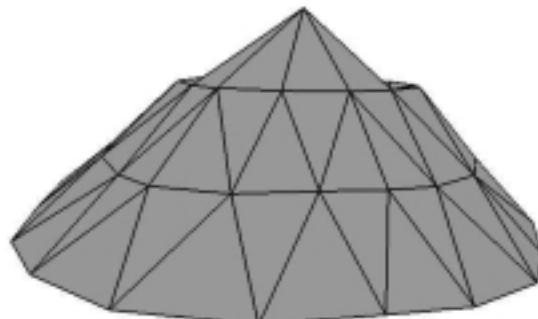


Figure 11. The side view of a TIN model

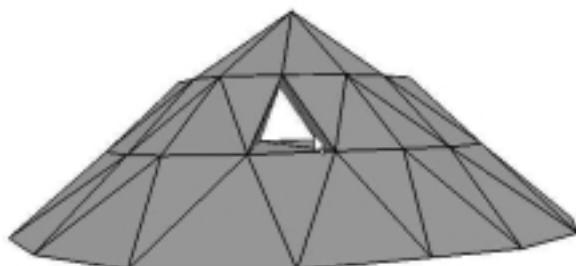


Figure 12. A hole on the TIN

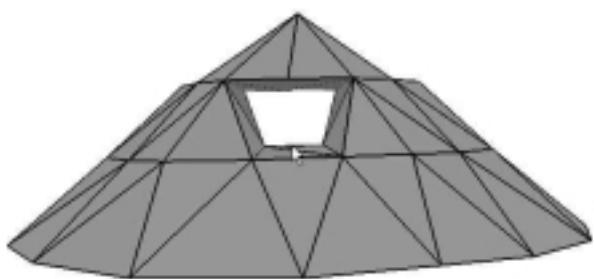


Figure 13. The enlarged hole using “swap”

To kill the hole, we have to use “KEF” to kill all the faces inside the hole until only one face left. Then use “KEHMF” to kill the hole, the edge and the face inside the hole. Two faces are created and one face is killed, therefore one face is added. The triangulation reverts to its original “solid state”. The code of “KEHMF” is the same as “KEF”. We can use the same code as creating a hole in order to build a bridge. Fig. 14 shows a top view of a TIN model and fig. 15 shows a bridge on the TIN. Fig. 16 shows an enlarged bridge formed by using “swap”. We can use the same code for killing the hole on TIN to kill the bridge.

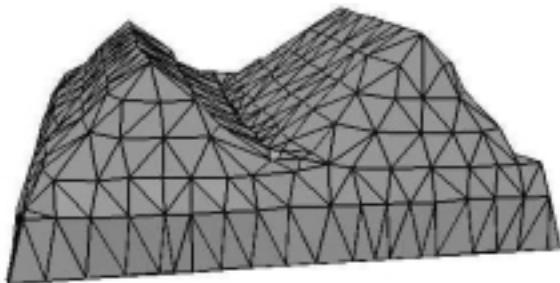


Figure 14. Top view of TIN model

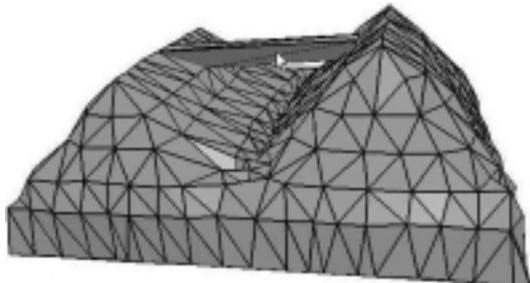


Figure 15. A bridge on the TIN

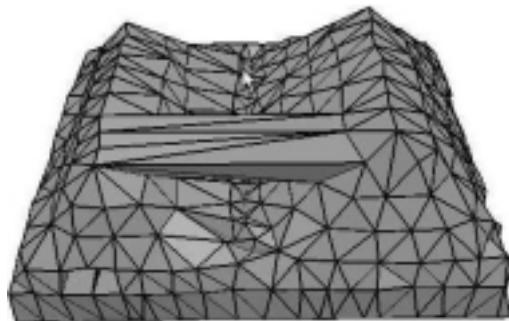


Figure 16. An enlarged bridge using “swap”

To extrude a building from an existing TIN model, we use “MEF”’s to make edges and faces between the top of the building and the ground floor. We need to select one triangle from the TIN model and give a specified height value (30). Fig. 17 shows the first step of “MEF” to make a new face on the selected triangle. Both of the faces are running in anti-clockwise order.

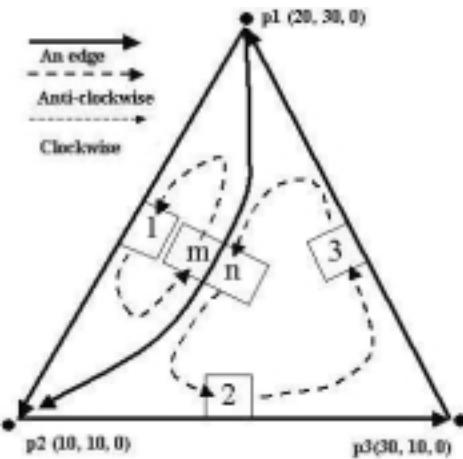


Figure 17. “MEF” on the selected triangle

We use “SEMV” to create a new point ( $p_4$ ) and split the edge into two pieces in fig. 18. The height of the new point is the input height value of the building. The  $x$  and  $y$  value of  $p_4$  are the same as  $p_1$  because  $p_4$  is vertically above  $p_1$ . After “SEMV” all edges in the two faces are running:

- $r \Rightarrow 2 \Rightarrow 3 \Rightarrow n \Rightarrow r$
- $1 \Rightarrow s \Rightarrow m \Rightarrow 1$  (running in clockwise order when looking from inside)

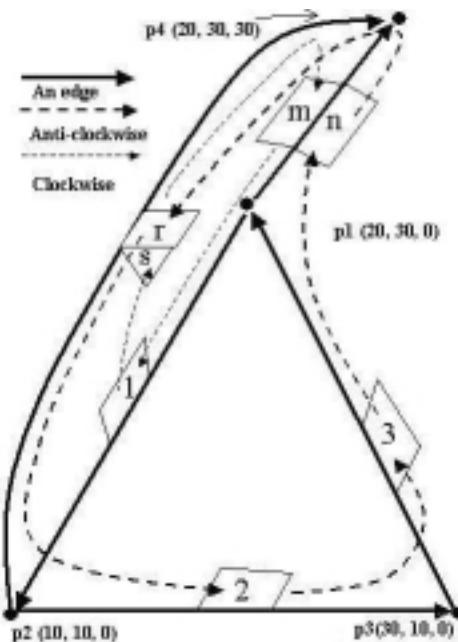


Figure 18. Use “SEMV” to split the edge

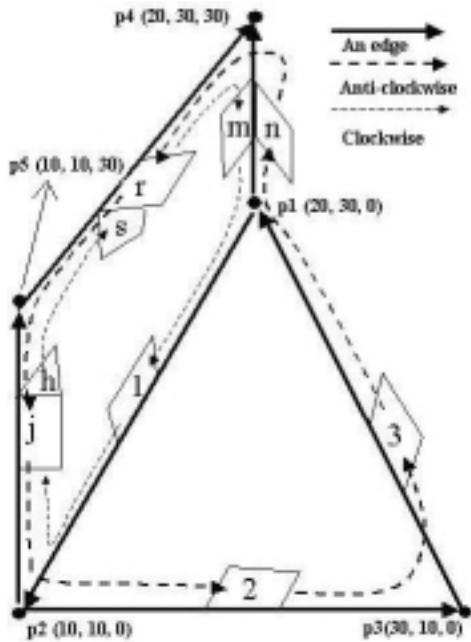


Figure 19. Use “SEMV” to reshape the face into rectangle

To reshape the face into rectangle, we need to use “SEMV” to add a new point and an edge in fig. 19. One face is created using “MEF”. There are three faces in fig. 20. All of them are running in anti-clockwise when you are looking from the outside.

- 1 => h => s => m => 1
- 2 => b => r => j => 2
- 3 => n => a => 3 (New face)

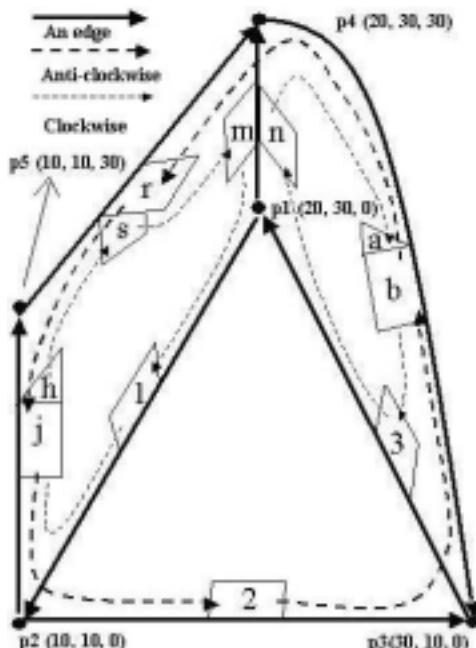


Figure 20. Make a new face using “MEF”

Fig. 21 shows after using “SEMV” to reshape the face into rectangle. Use “MEF” to add an edge and a face. Three faces are on the side of the building. One face is on the top of the building. All of them are running in anti-clockwise order when you are looking from the outside in fig. 22.

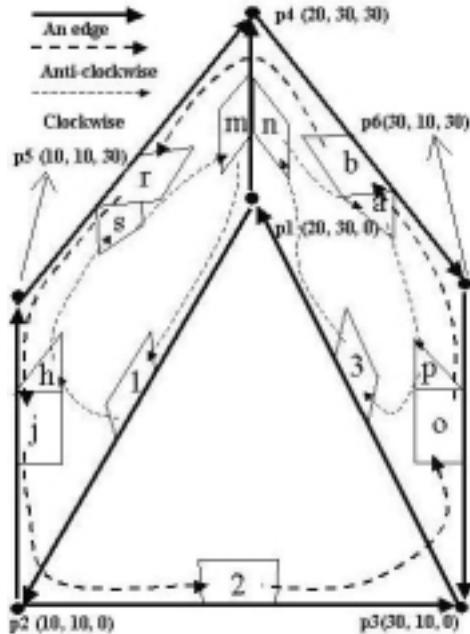


Figure 21. Use “SEMV” to reshape the face into rectangle

There are four faces on the building. Connectivity is preserved. Three more “MEF”’s are used to split the side faces of the building into triangles.

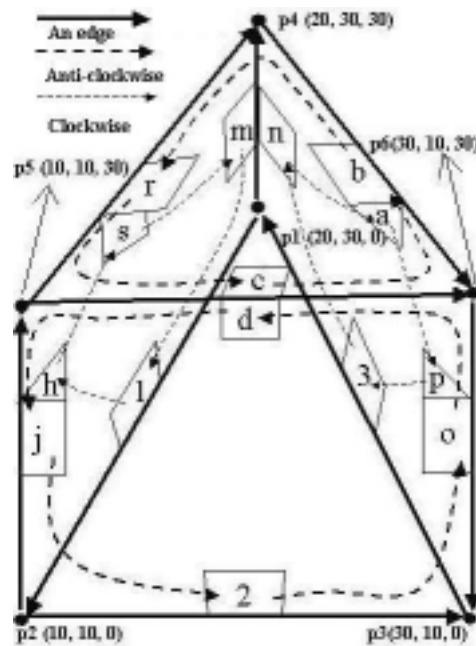


Figure 22. Use “MEF” to split a face

Fig. 23 shows the TIN model with one building. Fig. 24 shows the TIN with two multi-storey buildings. Fig. 25 shows a bridge connecting these two multi-storey buildings.

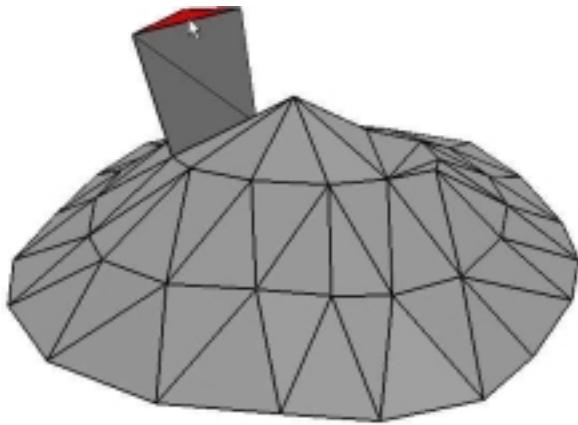


Figure 23. One building is extracted from a TIN

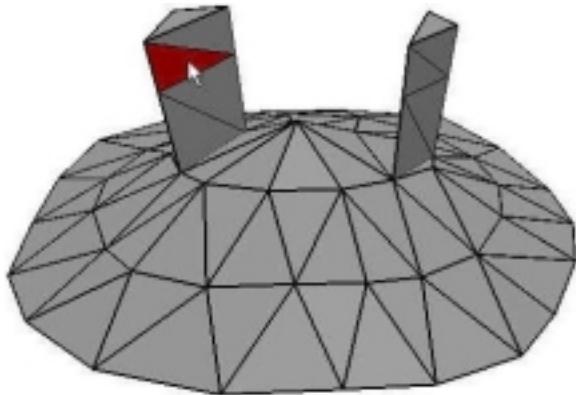


Figure 24. Two multi-storey buildings

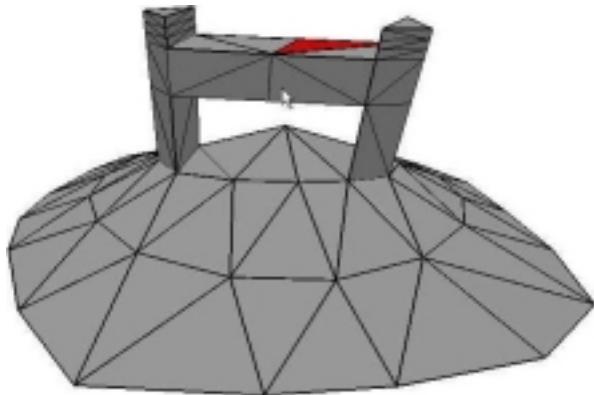


Figure 25. A bridge connects two multi-storey buildings

## 9. RELATION TO PREVIOUS WORK

The work we describe here has several steps, each of them new within a particular context:

1. Euler Operators, as used in CAD systems, are usually based on the Winged-Edge structure of (Baumgart, 1972).

The implementations of (Mantyla, 1981; 1988) indicate the complexity of this approach. We show here that the Quad-Edge structure of (Guibas and Stolfi, 1985) is a more natural, and much simpler, methodology. This is of potential interest to the CAD and Computer Graphics communities.

2. For the GIS community, we show the close relation between TIN modelling, b-rep structures from CAD, and Computer Graphics mesh generation. By eliminating one CAD primitive (holes in faces) and restricting ourselves to triangular elements, Euler Operators may be directly ported to GIS.

3. Once TIN operations are expressed as Euler Operators, additional topological operations may be performed directly, in particular the creation and deletion of holes permitting the interactive formation of bridges, tunnels, etc. To our knowledge, the introduction of some CAD techniques into TIN modelling has never been suggested before.

## 10. CONCLUSIONS

Thus, in summary, we are following a CAD-based b-rep sense of connectedness that uses Euler Operators to build the well-known TIN model, and extends it to permit holes and bridges – all based on the Quad-Edge structure. We show the validity and the implementation of these operators in preserving the connectedness of our “2.75D” TIN model. Operational details concerning the navigation within the mesh, and the selection of individual elements, have not yet been finalized. Nevertheless, the results conform well to the basic concepts of model representation within OpenGL, they depend on very similar data structures to those currently available for TINs, and they greatly simplify the implementation of a basic CAD system. We feel that this juxtaposition of computer science, CAD and GIS techniques opens up a variety of interesting possibilities, not least the manipulation of terrain models to represent some of the more complicated forms of human landscape modification.

Having now based our TIN model on a small set of simply-implemented Euler Operators, we are free to follow the CAD approach and build additional high-level functions, to form specific features (e.g. buildings) in our triangulation structure.

## ACKNOWLEDGE:

The authors would like to acknowledge the financial support of a research studentship from Hong Kong Polytechnic University.

## REFERENCES:

- Baumgart, B.G. (1972): Winged edge polyhedron representation. Stanford University Computer Science Department, Stanford Artificial Intelligence Report No. CS-320.
- Braid, I.C., R.C. Hillyard, and I.A. Stroud (1978): Stepwise Construction of Polyhedra in Geometric Modelling. In: Mathematical Methods in Computer Graphics and Design, Ed K.W. Brodlie: Academic Press of Computer Laboratory, University of Leicester, Leicester, England, pp. 123-141.

- Gold, C., (1979): Triangulation-Based Terrain Modelling-Where are we now? Proceedings: Auto-Carto 4, International Symposium on Cartography and Computing; Baltimore, MD, 1979, pp. 104-111.
- Gold, C., (1998): The Quad-Arc Data Structure. Proceedings: 8th International Symposium on Spatial Data Handling; Vancouver, BC, pp. 713-724.
- Guibas, L., and J. Stolfi (1985): Primitives for the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams. *ACM Transactions on Graphics*, Vol. 4, No. 2, pp. 74-123.
- Lee, K. (1999): Principles of CAD/ CAM/ CAE Systems. Seoul National University. Korea.
- Mantyla, M. (1981): Methodological Background of the Geometric Workbench. Helsinki University of Technology, Finland.
- Mantyla, M. (1988): An Introduction to Solid Modeling. Helsinki University of Technology, Finland.
- Masuda, H., Shimada, K., Numao, M., and Kawabe, S. (1990): A Mathematical Theory and Applications of Non-manifold Geometric Modelling. In: Advanced Geometric Modeling for Engineering Applications North-Holland, Amsterdam
- Peucker, T. K., R. J., Fowler, J. J., Little, and D. M., Mark, 1978: The triangulated irregular network. In: Proceedings Digital Terrain Models Symposium (St. Louis: American Society for Photogrammetry), pp. 516-532.
- Tse, O.C., and C. Gold (2001): Terrain, Dinosaurs and Cadastres - Options for Three-Dimensional Modelling. Proceedings, International Workshop on "3D Cadastres", Delft, Netherlands, November, 2001.
- van Kreveld, M. (1997): Digital elevation models and TIN algorithms. In: M. van Kreveld, J. Nievergelt, T. Roos, and P. Widmayer (eds.). Algorithmic Foundations of Geographic Information Systems, number 1340 in Lecture Notes in Computer Science (tutorials), pp. 37-78. Springer-Verlag, Berlin.
- Weiler, K. J. (1986): Topological structures for geometric modeling. PhD thesis, Rensselaer Polytechnic Institute, University Microfilms International, New York, U.S.A.
- Weiler, K. J. (1988): Boundary Graph Operators for Nonmanifold Geometric Modeling Topology Representations. In: Geometric Modeling for CAD Applications, Elsevier Science, Amsterdam.
- Zeid, I., (1991): CAD/ CAM theory and practice. McGraw-Hill, New York, pp. 368-388