HYBRID TERRAIN VISUALIZATION BASED ON LOCAL TESSELLATIONS

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Keywords: Hybrid terrain representation, Interactive visualization, Tessellation, Convexification.

Abstract: Hybrid terrain models represent an effective approach to combine geographic data with different acquisition properties. Terrain models constituted by regular grid elevation data may locally integrate detailed TIN meshes to represent morphologically complex terrain features and artificial objects. However, direct rendering of hybrid terrain models poses additional difficulties: holes and geometric discontinuities between the borders of the different parts would appear in the images. In this paper we present two new software based proposals for efficient hybrid terrain visualization. Both proposals generate high-quality geometrically continuous models and support multiresolution methods over regular grids.

1 INTRODUCTION

Interactive visualization of large Digital Terrain Models (DTM) is an important challenge in the field of computer graphics. Due to the increasing utilization of applications that use 3D geographic models on a large scale –such as Geographic Information Systems (GIS), cartography, urban planning, virtual reality and computer games– in recent years, different methods to optimize the process of visualization have been successfully developed (VTerrain, 2008). Most of the optimization techniques are based on employing several representations of the original model with different Level Of Detail (LOD) (Luebke et al., 2002).

An interesting situation arises when one base representation of the terrain exists together with another, in a different type of representation, for areas requiring a finer sampling, such as topographically complex terrain features and artificial man-made microstructures. This permits the enhancement of existing regular terrains by adding details to specific regions of interest without having to increase the overall resolution or having to convert the whole terrain model into a finer and irregular representation. Microstructures integrated in grid-based terrain models also improve the graphical and perceptual quality of visualized terrain models, since they provide a more precise and adequate geometry, shading, and illumination of morphologically important terrain features (typically affecting less than 20% of the complete terrain surface).

Proposals analyzing the problem of directly representing hybrid terrain models have recently appeared. An adaptive tessellation procedure to connect both meshes is suggested in (Dykes et al., 2005) to avoid discontinuities in the junction between representations. However, no specific tessellation algorithms were proposed in these works. Based on this idea, a technique for interactive visualization of hybrid meshes was presented in (Bóo et al., 2007; Amor and Bóo, 2008). The main characteristic of this Hybrid Meshing (HM) algorithm is that an efficient LOD level independent scheme is used for representing the local adaptive triangulation between mesh borders.

In this paper we present two software oriented algorithms for the visualization of hybrid terrains. Our proposals, inspired in the hardware oriented algorithm developed in (Bóo et al., 2007; Amor and Bóo, 2008), are based on the generation of the additional required triangles following a cell-based strategy. Specifically, we have employed two algorithms to generate those triangles. The first one computes local tessellations using the incremental randomized triangulation algorithm for triangulating polygons (Seidel, 1991). The second one adapts the HM algorithm to a software im-

Paredes E., Lema C., Amor M. and Bóo M. (2009).
HYBRID TERRAIN VISUALIZATION BASED ON LOCAL TESSELLATIONS.
In *Proceedings of the Fourth International Conference on Computer Graphics Theory and Applications*, pages 64-69
DOI: 10.5220/0001768200640069

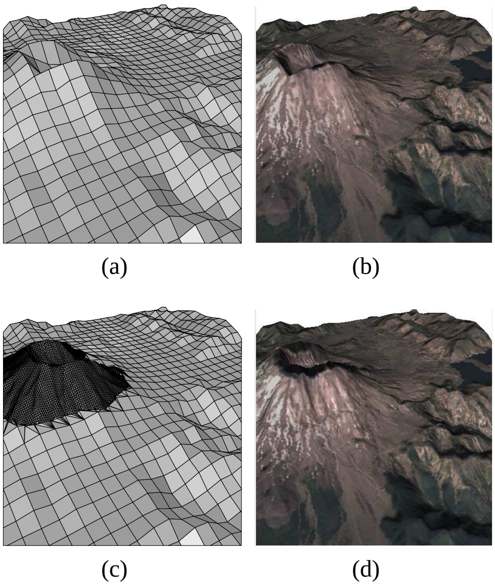


Figure 1: Hybrid terrain model. (a) Grid (b) Grid with texture (c) Hybrid model (d) Hybrid model with texture.

plementation. A performance evaluation of our experimental implementation of both methods and a comparison between them is presented here.

2 HYBRID REPRESENTATION OF TERRAIN MESHES

Digital Terrain Models are represented in different ways depending on several factors such as the nature of the capturing technology, input data, or application domain. Digital Elevation Model (DEM) (Luebke et al., 2002) is a simple and widely employed representation method that stores a collection of regularly spaced elevation samples of the terrain surface in a gridded 3D mesh. An alternative data model for terrain representation is the Triangulated Irregular Networks (TIN) (Luebke et al., 2002). TIN meshes approximate the terrain by a set of non-overlapping contiguous triangles, generated by connecting a finite set of irregularly spaced sampled data points.

Hybrid representation of terrain meshes integrates information from different data models, usually from DEM and TIN. These hybrid models act as a memory-efficient approach for detailing terrains with complex topographic structures. But, as data points are usually provided from different measuring systems, a method to connect the data is required to avoid discontinuities in the junction of the meshes.

When real-time visualization is needed, multiresolution techniques are often used. However, including multiresolution in hybrid terrains implies that the connections between DEM and TIN models would depend on the LOD. Due to this dependence, precomputing and transmitting LOD-dependent information would not be optimal. The solution presented in (Yang et al., 2005) is based on the generation of a preprocessed mesh combining both representations. Specifically, the Delanuay triangulation of square tiles of the grid is performed according to the TIN information. The main disadvantage of this method is the implied modification of the original data.

We present in this paper a software oriented solution based on the local tessellation of the grid cells. Our proposal consists in generating additional triangles to join the models, following the strategy developed on (Bóo et al., 2007; Amor and Bóo, 2008). This strategy leads to the generation of high quality models, as it avoids any modification of the original data. Figure 1 shows an example of application. The first two subfigures present a grid and the enriched version with a texture. The last subfigures are based on the hybrid model representation. Note that the higher quality of the image is associated with the utilization of a detailed TIN model of the crater.

The final hybrid model is formed by the union of the grid and TIN in a single, coherent mesh. The generation is performed as follows: first, the entire TIN and non covered cells of the grid (*NC cells*) are directly rendered; next, completely covered grid cells (*CC cells*) are eliminated, as they will be replaced by the more detailed TIN data; finally, those grid cells partially covered (*PC cells*) by the TIN have to be adaptive tessellated. This local tessellation strategy was selected due to its simplicity and the relatively easy adaptation for use in conjunction with LOD systems. An interesting consequence of joining models through a local, cell-based strategy is that high quality triangulations are generated.

In this paper we work with two tessellation algorithms, based on the incremental randomized triangulation algorithm (Seidel, 1991) and a software implementation of the HM strategy suggested in (Bóo et al., 2007; Amor and Bóo, 2008).

3 PROPOSAL BASED ON THE INCREMENTAL RANDOMIZED TRIANGULATION METHOD

Our first proposal is based on the identification of the non covered part of each PC cell and the utilization of a standard polygon triangulation algorithm to connect the TIN and grid models. The first step is the

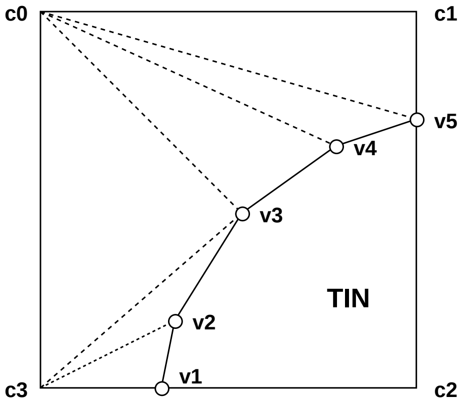


Figure 2: Corner tessellation example.

identification of the polygon made by the non-covered grid cell corners and the vertices of the TIN boundary falling into this cell. As shown in the example of Figure 2, the identification is performed on the XY projection of the meshes. In this example the polygon to be tessellated is made by the cell corners c_0, c_1, c_3 and the TIN boundary vertices $v_1 - v_5$. Note that to assure a cell-based tessellation the intersection vertices between TIN boundary and cell edges have to be included. In the example represented in Figure 2, vertices v_1 and v_5 were included for that purpose.

In the second step of the algorithm, the objective is to perform a fast triangulation locally for each PC cell. As the vertices of the grid in the cell may be different in each LOD, the tessellation is performed after extracting the level of detail selected by the multiresolution model. Consequently, the triangulations are LOD dependent and have to be completely recalculated every frame.

We have selected for our implementation, among all polygon tessellation methods, the Incremental Randomized Triangulation algorithm (Seidel, 1991). This algorithm has been widely implemented due to its simplicity and efficiency. Good results in terms of quality are obtained following this cell-based strategy as will be shown in Section 5.

4 PROPOSAL BASED ON THE HYBRID MESHING METHOD

The HM algorithm was presented in (Bóo et al., 2007; Amor and Bóo, 2008) as a hardware oriented method to achieve high performance and good quality in interactive visualization of hybrid terrains. The algorithm generates an efficient LOD level independent representation which is used for the adaptive triangulation of every PC cell of the model.

The HM algorithm has two main cores: the local convexification of the TIN and the adaptive tessellation of the resulting convex structure. The convexification of the TIN can be performed as a preprocessing step and the corresponding information efficiently encoded. As this information can be precomputed and encoded, the triangles associated with this step can be generated in run-time by simple decoding operations. On the other hand, the final tessellation to be executed in run-time is very simple, due to the convex structure of the TIN. This will achieve good results in terms of execution time for this algorithm.

4.1 Triangulation between Tin and Grid using Convex Tin Structures

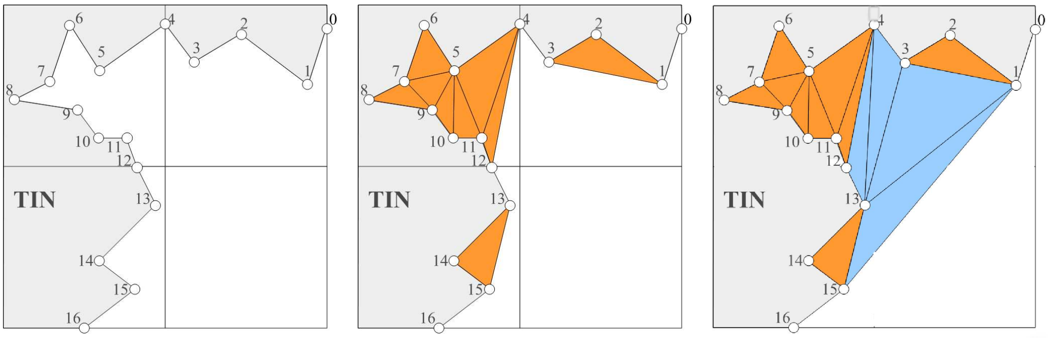
During the rendering process, the grid cells partially covered by a TIN mesh are connected with TIN boundary vertices. Assuming that the TIN boundary has been previously convexified, the method works generating triangles that connect uncovered cell corners of the grid with consecutive TIN vertices while the introduced triangle does not overlap with the TIN. The shift in the grid corner employed is easily detected by evaluating the angles between the corner and consecutive vertices of the TIN, which is efficiently implemented by testing the sign of the cross product of consecutive edges in the TIN boundary.

Consider the example shown in Figure 2 where a partially covered (PC) cell and the corresponding convex TIN silhouette are depicted. TIN boundary vertices $(v_1, v_2, v_3, v_4, v_5)$ and the cell corners uncovered by the TIN (c_3, c_0, c_1) are assumed to be processed in a clockwise order. The HM algorithm acts by connecting the list of corners with the list of vertices following a sequential order. This way, c_3 corner is consecutively connected with the vertices of the boundary where possible. In this example corner c_3 is connected with vertices v_1, v_2 and v_3, but not with v_4 because the new triangle (c_3, v_3, v_4) would overlap with the TIN. Therefore, corner c_0 is then selected and connected with v_4 and with v_5.

4.2 Incremental Convexification

As the triangulation process requires a properly convexified TIN boundary to work without flaws, a convexification process for the TIN boundary is locally performed in each cell. The resulting convexified boundary is efficiently stored, for all different convexification levels, in a simple and lightweight data structure.

The convexification inside each cell has three steps: compute the convex hull of the TIN boundary



(a) (b) (c)

Figure 3: Four cells of a grid with the TIN silhouette. (a) Before convexification (b) Finest LOD level convexification (c) Coarser level convexification.

in the cell, identify concave cavities on the boundary and, finally, triangulate those cavities. Following this cell-based strategy and to assure a local tessellation, it is assumed that there is a vertex in every intersection point between the TIN boundary and the cell borders.

In the first step the convexification is performed for the finest grid resolution level. Figure 3(a) shows four cells corresponding to the finest resolution level of the grid and the corresponding TIN silhouette covering this area. The TIN is depicted in grey, the TIN boundary is explicitly marked and vertices on it are indicated with circles. The local convexification results are indicated in Figure 3(b). Local convex hulls are delimited by vertices $\{0,1,3,4\}$ (up-right cell), $\{4,12\}$ (up-left cell) and $\{12,13,15,16\}$ (down-left cell). Once the convex hull for each cell is determined, the triangles inside the caves are generated using any standard tessellation algorithm.

After computing the convex hull for all cells in the finest level of detail, the following coarser level is processed following an incremental strategy and the triangles generated in previous convexifications are preserved. Following the previous example of Figure 3(a), the next coarser level of detail is analyzed in Figure 3(c). In this figure, the new convexification triangles are shown and, with a different colour, the ones generated in previous steps. The new local convex hull is determined by vertices $\{0,1,15,16\}$. The procedure continues for each cell and each level of the grid until the coarsest level is processed.

4.3 Hybrid Model Representation

As has been shown previously, the key point of the HM algorithm for achieving good performance results is the compact and efficient representation of the convexified boundary information of the TIN. The simplicity of the tessellation procedure is directly related to this representation as well. As a result, and given a LOD, the corresponding triangles can be extracted from this representation in run-time by means of very simple decoding operations.

Together with this information, two additional lists are used to directly identify the cells and the vertices implied in the tessellation: the Grid Classification list and the Vertex Classification list. The first one permits the identification of the cells to be directly rendered and the cells to be tessellated. The second one indicates the TIN Boundary (TB) vertices to be employed in the local tessellation for each cell. In the following we summarize only the representation to encode the convexification triangles. A complete description of the representation can be found in (Bóo et al., 2007; Amor and Bóo, 2008).

To encode the convexification triangles the list of TB vertices together with some additional connectivity information is employed. Assuming that the TB is stored following a clockwise ring structure, the connectivity associated to each vertex indicates the distance (number of vertices) between that vertex and the most distant one in the ring connected to it. This way, if connectivity of vertex v_i is j, it means that the farthest vertex connected to it is $v_i + j$. Let us consider the example described in Figure 3(c) to illustrate this storing strategy. In that example the TB array is:

$$TB = \{0(1), 1(14), 2(1), 3(10), 4(9), 5(6), 6(1), 7(2), 8(1), 9(1), 10(1), 11(1), 12(1), 13(2), 14(1), 15(1), 16(1)\}$$

where the connectivity value of each vertex is indicated within brackets. For example, vertex 4, with a connectivity value of 9, is connected with vertex 13 and all the vertices between them that are not inside a nested cavity. In this case, connectivity values show two nested cavities: between 5 and 11 and between 7 and 9. The algorithm assumes a sequential connection of the starting vertex of a cavity to all the vertices inside it, but this connecting structure is broken if nested

Table 1: Size and complexity of the test scenes.

	Grid cells	TIN triangles
Scene 1	400	3144
Scene 2	400	1563
Scene 3	1089	9872
Scene 4	5445	49360

Table 2: Performance results obtained with both proposals.

	Triangles generated	Inc. triang. based proposal	HM based proposal
Scene 1	186	442 fps	1356 fps
Scene 2	158	523 fps	1776 fps
Scene 3	444	308 fps	753 fps
Scene 4	2220	46 fps	132 fps

caves exist. For this example, vertex 4 is connected to all vertices between 5 and 13, but not inside a nested cavity, that is: $\{6,7,9,10,11\}$, and so on.

As explained in (Bóo et al., 2007; Amor and Bóo, 2008) the connectivity values generated for the coarsest LOD can be employed for any other LOD, and this unified representation may be employed for the reconstruction of the convexification triangles associated with different levels of detail.

5 EXPERIMENTAL RESULTS

We have tested our two strategies employing a hybrid terrain visualization software that includes the two tessellation algorithms.

Test computer hardware is a Intel Core 2 Duo E6600 with 2 GB of RAM and a GeForce 8800GT 512 MB. We have used four different scenes in our testing. The first three of them are formed by a regular grid partially covered by a TIN patch. The last one is a synthetic model consisting of five copies of the meshes present in scene 3. The number of grid cells and TIN triangles of each scene is shown in Table 1.

The main results obtained with the two proposals are summarized in Table 2. The number of triangles generated to connect the different representation models (second column) is the same for the two methods. This is coherent with the fact that the polygons to be triangulated are the same for any method.

As is shown in the table, the HM based proposal (fourth column) clearly outperforms the one based on incremental randomized triangulation (third column). HM method is, in the worst scenery, 2.44 times faster, and it reaches the maximum difference in *Scene 1*, where it is 3.40 times faster. This is a direct consequence of using the preprocessed connectivity information of the TIN boundary in the HM algorithm, to generate the adaptive tessellation during run-time. As the method based on the incremental randomized triangulation does not perform any preprocessing of the meshes, the tessellation is computed directly from the selected vertices of the boundaries for each grid cell.

Table 3: Average compactness value of the triangles obtained with both proposals.

	Inc. triang. based proposal	HM based proposal
Scene 1	0,53	0,49
Scene 2	0,53	0,47
Scene 3	0,49	0,49

With respect to the quality of the triangulation, high quality models can be generated with both methods. An example of application is shown in Figure 4. These are the resulting models when a detailed TIN is applied to the scenes 1, 2 and 3. For both algorithms the meshes are softly joined and the connections are performed locally to each cell. The triangles generated are small and all the holes and cracks in the borders are eliminated. Despite the fact that the triangles generated with both methods are different, in terms of visual quality they are in fact quite similar. This fact is also shown in Table 3, where the average compactness values obtained for the two methods are presented. The *compactness* value (Gueziec, 1995) is an indication of the triangles shape, usually employed as a measure of quality, being zero for a degenerated triangle and one for an equilateral triangle. As shown in the table, triangulations obtained with both algorithms are very similar. However, the high quality results obtained in terms of speed with the HM algorithm make it a better solution for hybrid terrain rendering.

6 CONCLUSIONS

In this paper we have presented two different solutions to the interactive visualization of hybrid terrain meshes. Both methods are based on a process of adaptive local tessellation between the boundaries of a multiresolution grid model and a detailed TIN mesh. Our first proposal is based on a standard polygon triangulation algorithm (Seidel, 1991) and represents a simple and direct approach to the problem: it connects the models by performing a triangulation between the grid cell corners and the TIN boundary vertices. The second proposal is based on the hardware oriented HM algorithm (Bóo et al., 2007; Amor and

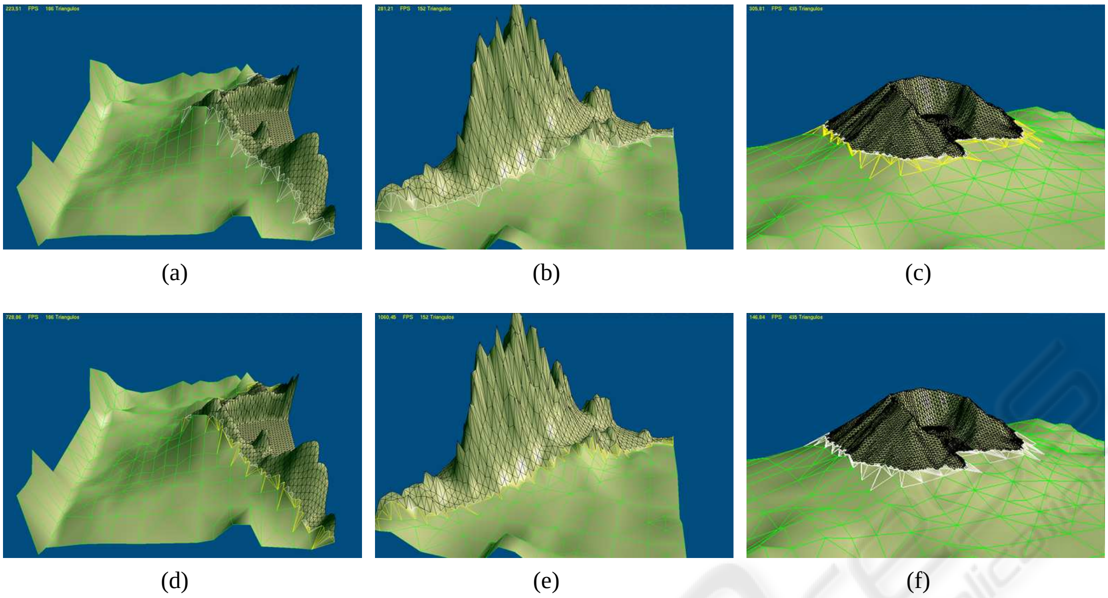


Figure 4: Adaptive tessellations generated by both proposals. Subfigures (a), (b) and (c) are generated by the proposal based on the incremental randomized triangulation. Subfigures (c), (d) and (e) are generated by HM based proposal.

Bóo, 2008), adapted to a software implementation.

The results of our tests indicate that both methods can obtain high quality meshes, without holes or any other triangulation artifact, in real-time. In terms of performance, however, HM based method runs several times better than standard polygon triangulation strategy. This important difference is caused by the efficiently encoded, unified representation of the convexification information in the TIN boundary for the HM algorithm. This means that part of the triangles are precomputed and decoded in run-time with simple operations. Additionally, the remaining triangles are generated through a straightforward procedure.

ACKNOWLEDGEMENTS

This work was partially supported by the Ministry of Science and Technology of Spain under contract *TIN 2007-67537-C03*, the Ministry of Education and Science of Spain under the contract *MEC TIN2004-07797-C02*, Xunta de Galicia under the contracts *08TIC0011206PR* and *Programa de consolidación y estructuración de unidades de investigación competitivas*, and also supported by the *High Performance Computing Galician Thematic Network (G-HPC)*.

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