Wavelet Analysis for a New Multiresolution Model for Large-Scale Textured Terrains

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ABSTRACT

Large terrain databases require a great number of polygons and textures. In consequence, transmission of terrain data over slow networks is still worrying. Multiresolution models allow progressive transmission, that is, the transmission of a simple model followed by successive refinements. In this work we describe a new multiresolution model called Geometric-Textured Bitree (GTB) that enables progressive transmission of both geometry and textures of a terrain model. Wavelet Multiresolution Analysis is applied in different steps of the process: selection of geometric points, texture classification and segmentation. An innovative texture synthesis process based on Wavelet classification is used in the reconstruction of the texture model.

Keywords
Progressive Transmission, Quadtree Triangulation, Multiresolution Model, Multiresolution Analysis, Wavelets, Texture Classification and Segmentation, Texture synthesis

1. INTRODUCTION

Multiresolution models provide different Level-Of-Details (LODs) of an object. Although large-scale terrain models require a great number of polygons and large images for textures, it is possible to use a multiresolution representation to obtain real-time visualisation and progressive transmission over networks.

Most of the previous work in multiresolution models only considers the geometry of an object and, at most, also attributes such as colour. In this work we propose a multiresolution model called *Geometric-Textured Bitree (GTB)* which considers both the geometry and the texture of a terrain.

The *Wavelet* transform produces a hierarchical decomposition of functions. According to Mallat [Mal89] a function is described by means of a low resolution function plus a series of details from low to high resolution. *Wavelets* provide means of frequency and space analysis. We focused them on multiresolution geometric models and multiresolution images.

A lot of work is carried out in the different related topics:

Wavelet Multiresolution Analysis: Gross [Gro96] uses Wavelets as a criterion for removal of vertices. Certain et al [Cer96] applies multiresolution Wavelet analysis to capture geometry and colour.

In addition, Wavelets are used for lossy and lossless image compression in algorithms such as *EZW* (*Embedded Zerotree Wavelet*) [Sha93] and the new standard *JPEG2000* [Tau02].

Wavelet-based Classification/Segmentation: A lot of work has been done on texture characterisation by means of Wavelet analysis in [Cha93] [Gro97] [Fat95] [Sim98]. Generally, Wavelets, Wavelet packets and tree-structured decomposition are used in addition to first and second order statistics. The problems with these approaches are the high dimension of the characteristic vector and the need for extra time to compute statistics. At the expense of a lower discrimination power we use a simpler scheme called progressive classification based on a characteristic vector formed with the RGB wavelet coefficients.

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Multiresolution Images: The coloured triangulation approach provides an adaptive sampling of an image by means of general triangulation [Dar96][Hop96]. A plain colour is assigned to each triangle and progressive refinement is possible by adding more samples.

Texture Synthesis and Generation: Simoncelli [Sim98] synthesizes new images by using the joint-probabilities of Wavelet coefficients. De Bonet [DeB97] synthesizes new textures by permuting similar regions based on the joint occurrence of several features through different resolution levels of the Laplacian pyramid.

Another texture generation process is based on repeteadly pasting texture patterns over a triangulated mesh [Ney99] [Pra00] but, generally, continuity considerations must be specified by the user.

Progressive Transmission: Hoppe introduces *progressive meshes* [Hop96] and applies it to a height field [Hop98]; Certain [Cer96] describes an application for transmitting coloured meshes over the Internet.

The contribution of the work presented in this paper is to propose a multiresolution model for both geometry and texture. We apply Wavelet Multiresolution Analysis in different steps of the process: selection of geometric points, texture classification and segmentation. Besides, a new texture synthesis process based on Wavelet classification is used in the reconstruction of the texture model.

Section 2 presents the overall architecture and general process undertaken. Sections 3 and 4 describe the geometric and texturemodel. Section 5 and 6 respectively present progressive transmission and reconstruction. Section 7 presents the results and section 8 gives the conclusion and future work.

2. ARCHITECTURE OVERVIEW

A terrain model is generally a height field, that is, a matrix of points that are distributed regularly on a two-dimensional grid. Texture information is in general a satellite image composed of different natural textures. The proposed multiresolution model Geometric-Textured Bitree (GTB) enables progressive transmission of both geometry and textures of a terrain model.

The general client-server architecture is shown in colour plates A and B. The server stores the topography and the texture of a terrain and, attending to a client's request, it processes both the geometric and texture models according to the selected level of detail. After that, it transmits a progressive coding of both types of data. The client decodes the stream and progressively reconstructs the geometry and texture of the terrain model.

The details of each of the processes involved are as follows:

- *Geometric model processing:* the original topography is a height field. The server obtains a Wavelet decomposition of the height field by means of a *Lifting Scheme* [Scr96]. To simplify the model points with a criterion based on the coefficient values are eliminated. After that, the selected points are organised according to the triangle hierarchy called Bitree [Abá99].

- *Texture model processing:* the server makes a Wavelet representation of the texture image by means of a Lifting Scheme. Texture classification of the coefficients of each level is carried out in order to obtain a segmentation of the original image in different texture classes. Each texture class is represented with a small image extracted from the original one, called the texture pattern.

- *Progressive Transmission:* we propose an algorithm to progressively transmit the GTB. The geometric information only includes the height values of the selected points ordered according to the Bitree hierarchy. The texture information is composed of both the texture patterns of the segmentation classes and also segmentation information. In order to transmit the latter, the server triangulates the segmentation image to obtain a Bitree hierarchy of triangles with a texture class assigned to each one.

- *Reconstruction:* the client progressively reconstructs the terrain model while receiving geometric and textural information. Height values are received and the position in the height field grid is deduced from the order of reception. A Bitree triangulation of the points is refined while receiving the stream. At the same time, the texture class assigned to each triangle is received and also the representative texture pattern of the class the first time it is referenced. Then, the triangles are filled with a synthetic texture from the correspondent texture pattern.

3. GEOMETRIC MODEL

The goal of a simplification surface process is to obtain a reduced model that uses fewer polygons and that approximates the original surface to a certain degree. It is desirable that the simplification process be adaptive to the terrain structure because regions with fast geometry changes have to be modelled with more triangles per area unit than a low curvature region.

3.1. Selection of Points

We select points according to a criterion based on *Wavelet* coefficients. The steps in the process for selection of points are the following:

1- To decompose the height field data by means of a *Wavelet* transform, we apply the Lifting Scheme with a depth of N steps.

2- To analyse Wavelet coefficients level by level. If the coefficients related to a set of 4-neighbouring points satisfy certain conditions, the set of points are replaced with only one.

The original points are grouped and related to the lifting coefficients according to their position and level. Each set of 2x2-neighbouring points in the original data is related to three corresponding coefficients in LH, HL and HH bands of level 1 of the Wavelet transform (figure 1). Considering the locality property of the Wavelet transform, each set of 2x2-neighbouring coefficients in each band are related to one parent coefficient in the corresponding next level band (figure 1.b.). By combining both relationships, each set of $2^i x 2^i$-neighbouring points in the original image relates to three corresponding coefficients in LH, HL and HH bands of the level i of the Wavelet transform. Finally, each set of $2^i x 2^i$-neighbouring points in the original image is the arrangement of 2x2 sets of $2^{i-1} x 2^{i-1}$-neighbouring points, which are called child groups of the level i group.

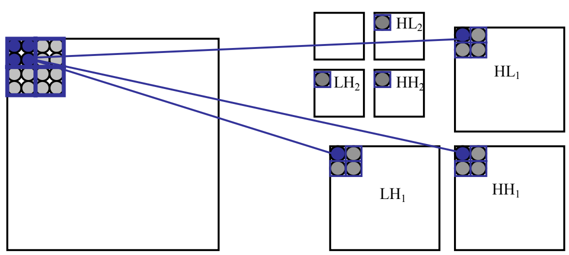


Figure 1. Relation between points in the original image (a) and coefficients in the Wavelet decomposition (b)

Each set Gj^i of $2^i x 2^i$-neighbouring points in the original image is analyzed to see if it can be replaced by only one point. To simplify a group Gj^i the two following conditions have to be satisfied:

1. $(|c_j^{banda\ i}| < threshold)$

where $c_j^{banda\ i}$ *is the corresponding coefficient in banda i, with banda i*$\in \{ LH_i ,HL_i,HH_i\}$ *and i is the level.*

2. If level i > 1, child groups G_1^{i-1}, G_2^{i-1}, G_3^{i-1}, G_4^{i-1} *of level (i-1) have to satisfy condition 1. If level i=1 this condition is satisfied.*

If both conditions are satisfied then the $2^i x 2^i$ points of group Gj^i are replaced by the upper-left point.

3.2. Triangulation of Points

After the points are selected they are then triangulated with the *Bitree* triangulation presented in our previous work [Abá99]. *Bitree* is a non-restricted adaptive hierarchical triangulation for height fields. The main features of *Bitree* are listed below (for details refer to the publication referenced above):

- Implicit hierarchy of triangles
- Non-restricted selection of points
- Adaptive Level-Of-Details
- It systematically derives the implementation with *triangle strips* [Eva96]
- *Cracks-free* triangulation with *"fictitious"* points

Similar triangulation methods are used by Lindstrom [Lin02]. The main difference between these and the Quadtree triangulation [Paj98] [Gro96] is that, with our scheme, it is not necessary to restrict the selection of points to avoid cracks. On the contrary, Bitree adds *fictitious* points to solve this problem. A fictitious point is the middle point of a triangle hypotenuse and its height is interpolated between the hypotenuse extremes. This means that the height is deducible and, in consequence, there is no need to store or transmit it.

4. TEXTURES MODEL

A *Wavelet* transform decomposes a function in different Levels-Of-Detail. It provides frequency and space analysis. In this work, multiresolution *Wavelet* analysis of textures is carried out with two different purposes:

- *Macro-level:* we analyse the texture image that is to be mapped to the geometric model. We segment this image with a texture classification process based on characteristics from *Wavelet* analysis. Then, we locate and extract small regions classified with the same texture, called *patterns*.
- *Micro-level:* in the transmission phase, the server sends texture *patterns* plus segmentation information. On the client's side, the image is finally reconstructed by synthesising every texture with a Wavelet-based classification process.

The *progressive classification* process has the following steps:

1. To apply the *Lifting scheme* to every channel of the RGB image with a depth of N levels or steps.
2. To form a characteristic vector for every pixel in each band of the hierarchical decomposition selected for the classification process. The vector has three components that are the *Lifting* coefficients of the corresponding RGB channels.

3. To progressively classify the pixels of each band starting with the lowest resolution level. This process considers the classification results obtained in the corresponding lower level, which is why the process is called progressive classification.

The bands to be considered can include only the low frequency level bands obtained at each step of the decomposition process. However, all the bands of the lifting scheme can be considered in the classification process. In this case, an additional classification is carried out with the classification results of each band as the characteristics for classifying the level. Good results are obtained with both options but the first one gives results with a lower number of classes.

The algorithm used for the classification is the *ISODATA (Iterative Self-Organising Data Analysis Techniques)*.

4.1. Segmentation

The original image is segmented by classifying every pixel with the progressive classification process explained above.

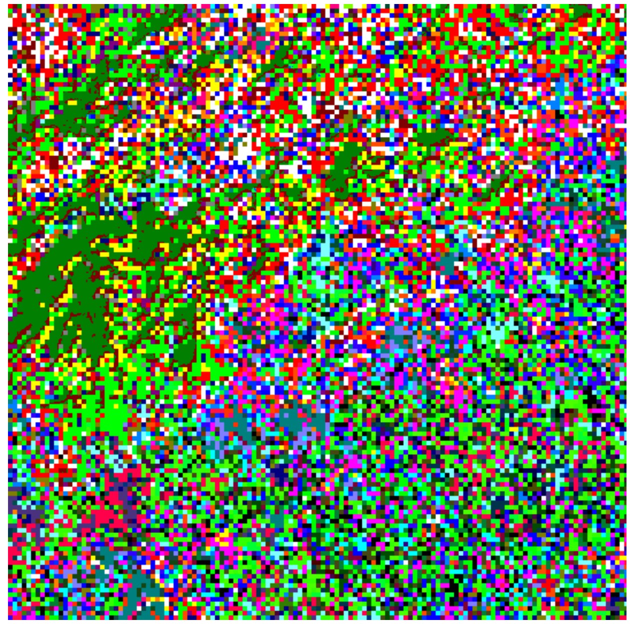
After the segmentation, *texture patterns* are extracted from the original image. A texture pattern is a rectangular region classified within the same class of texture.

If it is not possible to find patterns of a minimum size required, the corresponding class is eliminated. The pixels of this class are assigned to the class with the nearest representation vector.

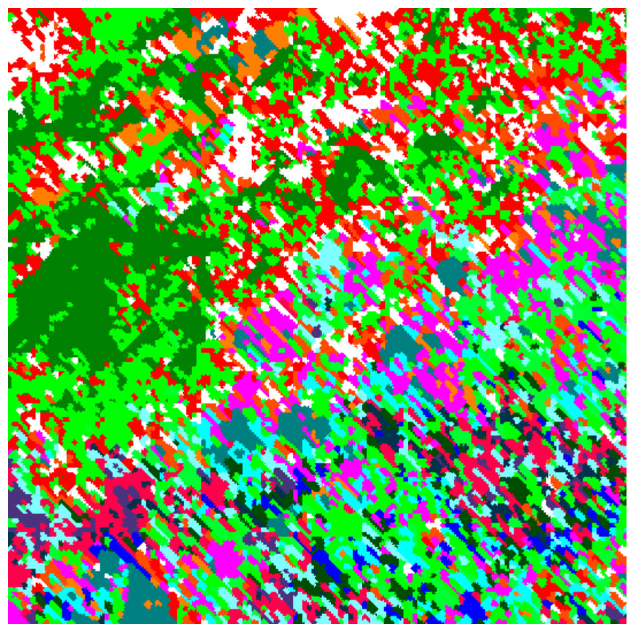
Figure 2 shows an image from LANDSAT satellite with a resolution of 30 metres per pixel and a size of 536 x 536 x 24 bits (287,296 pixels, 861,888 bytes).

Figure 2. Original image

The image is segmented after applying the progressive classification of the low frequency bands of a 2-level Wavelet CRF(13,7) and 81 classes are obtained (figure 3.a). After that the segmentation is modified by eliminating the classes with patterns smaller than 8x8 pixels,which results in 17 different texture classes (figure 3.b).



a)



b)

Figure 3. a) Original segmentation with 81 classes. b) Reduced segmentation with 17 classes.

4.2. Triangulation of the segmentation

After the pattern extraction phase, the segmented image is triangulated with *Bitree* coloured triangulation.

A triangle is considered to have a unique texture if the rate between the amount of its pixels classified with this texture and the total amount of its pixels exceeds a certain threshold. The triangulation starts with two initial triangles that are recursively divided if the textures are non uniform. If a triangle is uniformly textured within some tolerance, then the subdivision stops. Finally, we obtain a hierarchical triangulation with a texture class assigned to each triangle.

5. PROGRESSIVE TRANSMISSION

Progressive transmission of a model is the transmission of a basic approximation followed by successive refinements until the desired approximation is obtained.

After the geometrical and texture triangulation processes described above, we obtain a hierarchy of triangles with the following information associated to each triangle:

- the middle point of its hypotenuse;
- the texture class assigned to it.

The optimal transmission of a geometric model is to transmit the geometric points only without connectivity information. The GTB model tries to exploit the simple connectivity of *Bitree* to reduce *overhead* information.

In a height field the (x,y) values correspond to a regular grid in the XY space. Since the hierarchical *Bitree* triangulation classifies the (x,y) points on different levels according to their position in the grid, it is possible to make an implicit enumeration. Since the (x,y) position on the grid can be deduced from the order of reception, only the height values are transmitted.

As far as the geometric model is concerned, the information to be transmitted is:

- The state of the point;
- The heights of selected points only. Heights of fictitious points are deduced while the client reconstructs the *Bitree*.

With respect to the texture model, the information to be transmitted is:

- Texture patterns;
- Texture class-to-triangle mapping.

Whatever the area occupied by a texture in the original image is, only a fixed size texture pattern has to be transmitted for each texture class in the segmentation. Pattern images can be progressively transmitted by any known algorithm such as *EZW* or the recent standard *JPEG2000.*

Progressive transmission starts with the two upper triangles in the hierarchy and continues with the child triangles level by level. For each triangle, the following information is sent:

[<point state>[<height>]]

[F|<texture child 1><texture child 2>]

where

*<point state>*ε {*S,F,N*}is the state of the middle point of the triangle hypotenuse, which means:

S: selected
F: fictitious
N: non-selected

<height> is the height of the point if it was selected;

F indicates that the triangle is uniformly textured;

<texture child…> ε {*R,T,P,L*} is the texture information of a triangle child, which means:

T: a new texture is assigned and the image pattern has to be sent too;

R: an old texture is assigned and its reference is sent too;

P: same texture as its parent triangle;

L: same texture as the last triangle that was sent.

Note that both geometric or texture information can be absent. An N triangle means that geometric information will be absent for its children. Considering that the hypotenuse can be shared by two triangles, in this case the geometric information is sent only for the first one. Regarding textures, an F triangle means that its children's information will be absent.

6. RECONSTRUCTION

The client makes a progressive refinement of the model while receiving information about the triangles. At each step, the client awaits the following information for a triangle:

- geometric information only;
- texture information only;
- both geometric and texture information.

For each triangle the client receives with a selected point as geometric information, it updates the mesh by inserting the new point and dividing the corresponding triangle.

As to texture information, the client can receive the texture of the two children of the triangle. The reconstructed texture image is updated by filling the triangles with the corresponding reconstructed texture.

Reconstruction of texture combines both the ideas of repetition of patterns and texture synthesis.

The client receives a texture pattern image to represent each texture class localised in the segmentation. To reconstruct a large region filled with this texture, the client synthesises new texture patterns from the original one that it receives.

The synthesis process is based on Wavelet classification of the coefficients of the lifting pyramid of the image pattern (figure 4). In each band of the decomposition, coefficients with the same class are randomly permuted to generate the lifted pyramid of a new image. To avoid changes of colour in the synthesis result, the same position permutation is carried out in each RGB channel of the same band. To finally obtain a synthetic pattern the *inverse lifting scheme* is applied.

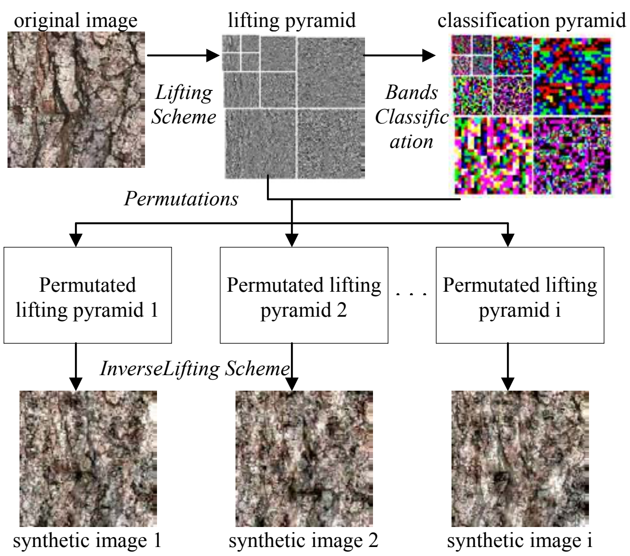


Figure 4. Synthesis process

A region that is larger than the pattern can be generated from new synthetic patterns. The simplest option to fill a region is by repeatedly pasting different syntheses of the original pattern, although better results are obtained by applying a process called *quadtree pasting* (figure 5). This process starts by analysing the original pattern to produce new synthetic patterns. A new image is generated by the arrangement of 2 by 2 synthesis and the synthesis process is repeated. Instead of analysing the new image to obtain the classification pyramid, this is obtained from a classification pyramid of the original pattern. This is carried out by duplicating each band in each dimension. To obtain the classification pyramid of a new image 2^i times greater than the original pattern, each band is copied 2^i times in each dimension.

Figure 6 shows the reconstruction of the original image of figure 2.

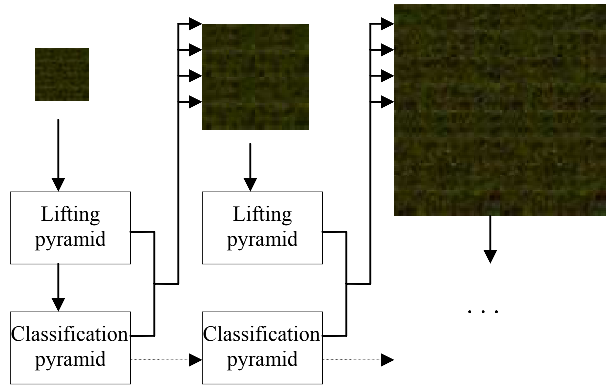


Figure 5. Synthetic region filling by *quadtree pasting*

Figure 6. Reconstruction of the original image of figure 2.

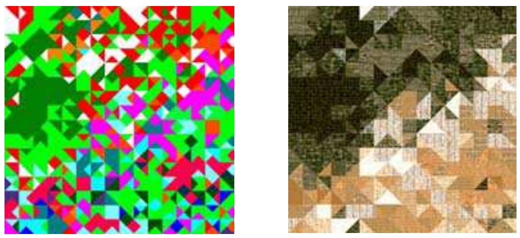
7. RESULTS

Figure 2 shows a texture image of 536 x 536 x 24 bits (287,296 pixels, 861,888 bytes). It is segmented (figure 3.a) with progressive classification of its low frequency bands of Wavelet CRF(13,7) with 2 depth levels. A total of 17 classes are obtained by eliminating classes with patterns smaller than 8 x 8 pixels (figure 3.b). The texture patterns extracted are 16 x 16 pixels and are synthesized by means of a classification based on Wavelet CRF(13,7) with 3 depth levels and 50 permutations in each band.

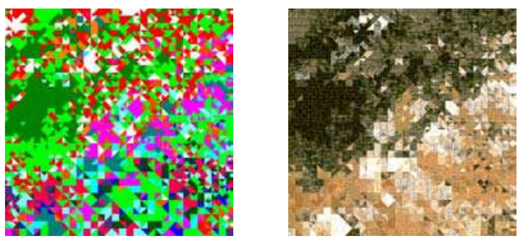
The completion of progressive transmission of the image needs 135 828 triangles and 24 320 bytes. Figure 7 shows the progression in the segmentation information and the synthetic reconstruction.

Topography is defined with a height field of 4097 x 4097 (an amount of 16,785,409 points) with a precision of 4 metres per point.

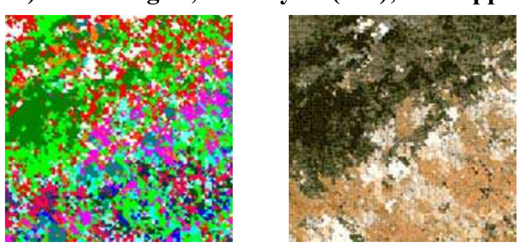
Height data is simplified with Wavelet CDF(2,2) with 4 depth levels and a threshold equal to 0. As a result, 42% of the points are selected. To triangulate them with *Bitree,* 5.9% fictitious points are added. The normalized *RMSE* (Root Mean Square Error) is 5.17E-05 and the maximum normalized absolute error is 0.0071 metres.



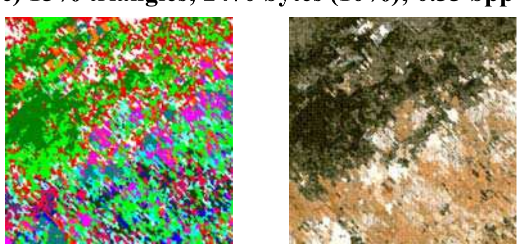
a) 1.5% triangles; 260 bytes (1%); 0.03 bpp



b) 5% triangles; 1012 bytes (4%); 0.13 bpp



c) 15% triangles; 2470 bytes (10%); 0.33 bpp



d) 75% triangles; 17 674 bytes (73%); 1.82 bpp

Figure 7. Progressive transmission (segmentation and synthetic reconstruction) with: 1.5%(a), 5%(b), 15%(c) and 75%(d) of triangles

8. CONCLUSION AND FUTURE WORK

We present a new model called GTB for progressive transmission of height and texture data of a terrain model.

The geometric model is first simplified by selecting points according to a Wavelet-based criterion. The selected points are triangulated by means of a Bitree hierarchical triangulation. Because it has an implicit enumeration of the points, this makes it possible to transmit only the height of the selected points. Overhead information is used to transmit the state of the points. This is useful to stop the refinement of a triangle when a point is marked as non-selected. In comparison with other models that transmit connectivity, the overhead information is reduced.

Transmission of simple texture patterns followed by a synthesis process allow the compression of the texture model.

The results obtained in the experiments are good enough to believe that the progressive transmission of GTB can bring us a good balance between visual quality and transmission costs.

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