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SEAMLESS JOINING OF TILES OF VARYING RESOLUTIONS FOR ONLINE 3D TERRAIN VISUALIZATION BY DWT DOMAIN SMOOTHING

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ABSTRACT

A novel context-based DWT domain smoothing strategy is being proposed for seamless tessellation of texture as well as the digital elevation model (DEM). In the use case, in perspective, the tessellation is heterogeneous in resolution with three different tile qualities or levels of detail (LOD), at a given instant, depending on the viewpoint distance, the time of rendering and hardware resources. The LOD is dependent on the multiresolution characteristic of wavelets from the now widely accepted JPEG2000 codec. Three different joining functions have been employed to create subband-sized masks for each of the tile subbands selected for smoothing. The results, obtained for a practical example, have been interesting in the sense that it eliminated the popping artifacts to a considerable extent without affecting the field of view at a given instant.

1. INTRODUCTION

The technology is advancing by leaps and bounds, but it is still away too far from catching up with the ever increasing rendering throughput of terrain visualization. The problem is exacerbated when the data is to be transferred over some network, especially in a client/server environment. With it comes another dimension in the shape of the client diversity in terms of memory, processing and bandwidth resources. For example, today's geo-browsers, like Google Earth or NASA's World Wind, do not take into account individual client characteristics and what one observes are lags and freezes for clients with low resources. All these factors necessitates some scalable data processing/structuring and the obvious choice is to create multiple levels of detail (LOD) by representing the shape at different levels of approximation. This is essential for the terrain tessellation adjustment as a function of the view parameters [1]. For LOD one can rely on the multiresolution nature of the discrete wavelet transform (DWT). It is better to employ some standard state-of-the-art DWT, like the now widely accepted JPEG2000 standard¹. Additional advantages of the JPEG2000 could be good compression and capability to transfer the data progressively.

As far as the rendering of large terrains is concerned, tile-based approaches have always been a preference. Our strategy is to render a texture/depth map tessellation from JPEG2000-coded tiles wherein only visible tiles are rendered and the focused ones, out of these, have the highest quality depending on the viewer's distance. As the viewer moves in, the tiles corresponding to the new view must be rendered at

and gradually refined in quality as the focus is coming near to it. This refinement is additive as more and more subbands are added to it, at runtime. The main challenge to this strategy is that the tile must be seamlessly stitched for both the texture and the digital elevation model (DEM) and the boundaries must be diluted enough to prevent popping artifacts. This phenomenon is observable even in the case of modern geo-browsers. While there have been many works on the seamless rendering of DEM, the efforts focusing on the textures are far less. In this paper, although we are more inclined to the texture, the DEM has also been treated as its integral part. In fact this work is a continuation of our earlier efforts about the synchronous unification of the DEM/texture pair through data hiding [2].

Our strategy is aimed at context-based smoothing of the tile boundaries. The smoothing is carried out at the subband level in the DWT domain by employing various smoothing masks. The lowest resolution tiles of the panorama are not treated while the mid-level resolution and the highest resolution tiles are modified to join them together. All this is explained in Section 3 after a brief account of the background literature in Section 2. We applied our strategy to a practical worst case example and the results are shown in Section 4 which is followed by the concluding remarks in Section 5.

2. BACKGROUND

Terrain LOD algorithms can be classified [1], on the basis of the hierarchical structure, into four groups, namely the triangulated irregular networks (TIN), bin-tree hierarchies, bin-tree regions and tiled blocks. The tessellation, in the last category, is carried out with the square tiles of different resolutions as has been done by Wagner [3]. But the process requires seamless stitching at the boundaries. According to Deb *et al* [4] the view frustum culling technique of [3] is not suited for the terrains with large height variations. They tweak the technique by having the projection on realtime average height of terrain for a client/server terrain streaming to handle heterogeneous clients. The blending factors are calculated on a per tile basis because of the use of a regular tile structure, thus, reducing the amount of computation. Special techniques based on mipmaps and clipmaps can be found in the literature. According to [5], "a mipmap is a collection of correlated images of increasingly reduced resolution arranged, in spirit, as a resolution pyramid whereas a clipmap is an updatable representation of a partial mipmap, in which each level has been clipped to a specified maximum size". Lossasso *et al* [1] breaks the terrains into geometric clipmaps of varying metric sizes which can be used as LODs through a

¹The ISO/IEC 15444-1 standard

view-centered hierarchy resulting in a simplified spatial and temporal inter-level continuity.

A thresholding scheme based on calculated ground sample distances is proposed in [6] with a nested LOD system for efficient seamless visualization of large datasets. In order to remove the T-junctions they have put forward a mesh refinement algorithm. Ueng and Chuang [7] propose a dike structure between two adjacent blocks, for a smooth blending between two meshes of different LOD. This approach is combined in [8] with heuristics to dynamically stitch the tile meshes together seamlessly. For the texture part they use high resolution aerial photos subjected to the similar LOD mechanism as described for the meshes. Larsen and Christensen [9] try to avoid popping for low-end users by exploiting the low-level hardware programmability in order to maintain interactive frame-rates. They claim their work as pioneering as far as a 'smooth' LOD implementation in commodity hardware is concerned.

Little attention has been paid to the texture images which require their own LOD structure. There have been proposals, like texture clipmaps [5], but texture tiling is usually preferred. The multiresolution technique, described in [10], presents static LOD terrain models, allowing for combination of multiple large scale textures of different size. The view-dependent texture management technique in [11] manages multiresolution textures in multiple caching levels - database, main memory and graphics card memory - which the authors claim to be suitable for hardware with limited resources. The approach of [12] includes dynamic texture loading for memory management and, combine several textures into atlases for avoiding too much texture switches [13]. Their computationally complex preprocessing part helps them to significantly reduce runtime rendering overhead.

3. THE SMOOTHING STRATEGY

3.1 Scenario

We are supposing a simplistic scenario of a panorama of 3×3 tiles. This use case will represent almost all the possibilities we will have in our application. An individual tile is large enough to circumscribe the field of view even if the observer is too far. In other words one can say that if the observer is too far, his/her view is limited to a 3×3 tessellation at maximum with all the tiles at their lowest resolutions but as soon as he/she draws closer, further detail is added to the tile of focus to improve its resolution. The smoothing process will be done only on a 3×3 tiles. The rest of the encompassing tiles are in the low resolution and hence there is no need to smooth them. The tessellation is heterogeneous in terms of resolution and a given tile can have one of the three qualities, namely high middle and low. The high quality resolution corresponds to the center which is the viewpoint focus. We are rendering the corners with low resolution and the 4-neighbors of the center with the middle resolution tiles. The terms high, low and middle are not static and their extent depends on the distance of observer from the view as well as the the time passed after the viewer changed his position. We are assuming this three quality environment because it reflects most of the possible cases in our application. Thus the 3×3 tessellation is not binding; rather it represents a simplistic worst-case scenario wherein three different quality tiles can be seamlessly rendered. There may be a tessellation having concentric square rings with each successive ring having a different quality [5] but we believe that at any

instant one would hardly be dealing with a rendering involving more than three resolutions. That is to say, our resolution set may contain a wide spectrum of resolutions but at a given time three of them would be rendered.

3.2 Viewpoint analysis

Our strategy is aimed at the seamless 3D visualization as a function of the network connection and the computing resources of the client. The resolution of various tiles in the tessellation is a function of its distance D between the observer and his/her focus on the terrain. As far as DEM is concerned, its quality is evaluated with the root mean square error (RMSE) in length units. As pointed out in some recently published works [14], even today the acquisition of the DEM, for 3D terrain visualization, is error prone and it is difficult to get a RMSE less than 1 meter in elevation. To calculate the maximum acceptable RMSE, for an optimal 3D visualization, we rely on the distance D (Fig. 1) and the visual acuity (VA) of the human visual system (HVS). Visual acuity is the spatial resolving capacity of the HVS. It may be thought of as the ability of the eye to see fine details. There are various ways to measure and specify visual acuity, depending on the type of acuity task used. VA is limited by diffraction, aberrations and photoreceptor density in the eye [15]. In this paper we assume for the HVS that the VA corresponds to an arc θ_{VA} of 1 minute ($1' = 1/60^\circ$). Then for a distance D we have a focus of diameter $2 \times D \times \tan(\theta_{VA})$ or more simplistically $E = 2 \times D \times \tan(\theta/2)$. Usually the field of view of the HVS is $\theta = 60^\circ$. For example if $E = 3200 m$ then $D = 2771.28 m$. For the 3D visualization, we should

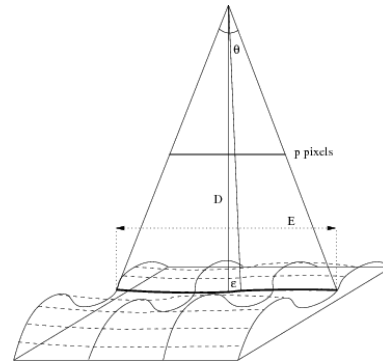


Figure 1: Visualization of a depth map from a viewpoint.

take into account of the resolution of the screen in pixels. As illustrated in Fig. 1, if we have an image or a screen with p pixels for each row, then the tolerable LOD error (ϵ) in p is:

$$\epsilon = \frac{E/2}{\tan(\theta/2)} \times \tan(\theta/p). \quad (1)$$

With $\theta = 60^\circ$, $E = 3200 m$ and a resolution of 320 pixels, a PDA for instance, we have $\epsilon = 9.07 m$. Then, in this context, for our application we can assume that a RMSE of about $9 m$ is acceptable for the visualization. Notice that we generate a conservative bound by placing an error of the maximum size as close to the viewer as possible with an orthogonal projection of the viewpoint on the depth map. We also assume that the range data model is globally flat and that the accuracy between the center and the border of the depth map is the same. In reality, the analysis should be different and part of the border should be cut as explained by [16] in a

particular case of a cylinder. Anyhow, the value of D would help us to reach a decision about the resolutions of various tiles in the tessellation.

3.3 The Level of Detail (LOD)

For the LOD we are relying on the multiresolution nature of DWT from the JPEG2000 codec. The reasons for choosing JPEG2000 are its scalability, its wide acceptance as a standard, its support to various wavelet forms for multiresolution, progressive transfer capability and last but not the least is its approximation paradigm for LOD. The various approximations do not differ in size but only in quality which is additive in nature. If each tile is DWTTed in the JPEG2000 codec at level L then a level- l ($\leq L$) approximate image is the one that is constructed with $(1/4^l) \times 100$ percent of the total coefficients. These coefficients correspond to the available lowest $3(L-l) + 1$ subbands and for the coefficients corresponding to the rest of the $3l$ subbands, zeros are stuffed. Subsequent application of L -level inverse DWT yields what is known as the l -approximate image. For example, level-0 approximate image is constructed from all the coefficients and level-2 approximate image is constructed from 6.12% of the count of the initial coefficients.

3.4 Smoothing functions

Let the high, the middle and the low resolution of our scenario correspond to l_h , l_m and l_l approximate images, respectively. The quality gap would essentially bring with it the popping artifacts at tile boundaries. To undo that, we are proposing a wavelet-domain context dependent smoothing strategy graphically explained in Fig. 2. At the corners (NW, NE, SW and SE) are the l_l -approximate images obtained from lowest $3(L-l_l) + 1$ subbands with the rest of $3l_l$ subbands being replaced by 0s. For the rest of the tiles one can partition their subbands into three sets. One, the lowest $3(L-l_l) + 1$ subbands will remain untouched since they represent the lowest rendered quality. Two, the highest $3l_h$ subbands of center tile (O) and $3l_m$ subbands of its 4-neighbors (E,W,N and S) are stuffed with 0s. Three, the remaining $3(l_l-l_h)$ and $3(l_l-l_m)$ subbands of central tile and its 4-neighbors, respectively. It is this third set (or its subset thereof) which will be subjected to the DWT domain treatment with three different smoothing functions on each subband individually:

1. for the left/right neighbors (W and E) of center use the horizontal smoothing function,
2. for the above/below neighbors (N and S) of center use the vertical smoothing function,
3. for the center (O) use the radial smoothing function.

Note that we are affecting the quality of only a small part on the periphery of the tile during a given smoothing process. For any given subband, the smoothing function creates a scalar multiplication mask (over $[0, 1]$) of the size of the subband. The horizontal smoothing mask would have a central band of rows of 1's. The thickness of this band depends on the maximum diameter, δ , of the view focus. If the subband belongs to the k th resolution level, then the thickness should be around $\delta/2^k$. Beyond the band of 1's the rows gradually attenuate on both sides approaching 0 at the periphery. Our horizontal smoothing function is described here in the form of algorithm 1. Along similar lines we can get a vertical smoothing mask which is nothing but a transpose of

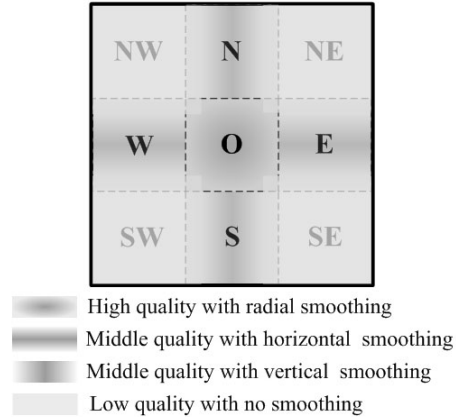


Figure 2: The Tessellation Scenario

Input: width(w) of a DWT domain square subband

Output: Horizontal $w \times w$ smoothing mask

```

1 begin
2    $\delta \leftarrow w/2$ ;
3    $min\_coeff \leftarrow 0$ ;
4   Initialize a vector  $B$  of size  $w * w$  to 1.0;
5   for  $j = 0$  to  $w/2 - \delta/2$  do
6      $min\_coeff \leftarrow min\_coeff + 2/(h - \delta)$ ;
7     for  $i = 0$  to  $w$  do
8        $B[i + w * j] \leftarrow min\_coeff$ ;
9     end
10  end
11  for  $i = 0$  to  $w * w/2$  do
12     $B[w * w - 1 - i] \leftarrow B[i]$ ;
13  end
14  return  $B$ ;
15  end

```

Algorithm 1: Horizontal Smoothing Function

the horizontal mask for a given subband. The radial smoothing mask is a bit tricky. We would have a center core of 1's having a diameter of about $\delta/2^k$ for a the subband of the k th resolution level. The shape of this core is more or less circular – octagonal, to be precise. Each ring of coefficients around the core would gradually attenuate approaching 0 at the corners and around 0.5 in the up/down and left/right directions. Algorithm 2 is the logical representation of our radial smoothing. After the smoothing treatment of a subset or all of the third group of subbands and inverse DWT one can have a seamless visualization of the type given in Fig. 2. In our application, we are using the same strategy for the DEM to avoid popping effect on elevation data.

4. RESULTS

We have applied our smoothing strategy to a practical example of 3072×3072 texture tessellation composed of 9 tiles of size 1024×1024 . The corresponding DEM tessellation at our disposal has a size of 96×96 with each of the nine tiles having 32×32 coefficients. The texture tiles were transformed at level-4 reversible DWT in a standard JPEG2000 encoder whereas the DEM tiles were subjected to reversible level-4 DWT simply. In our example visualization,

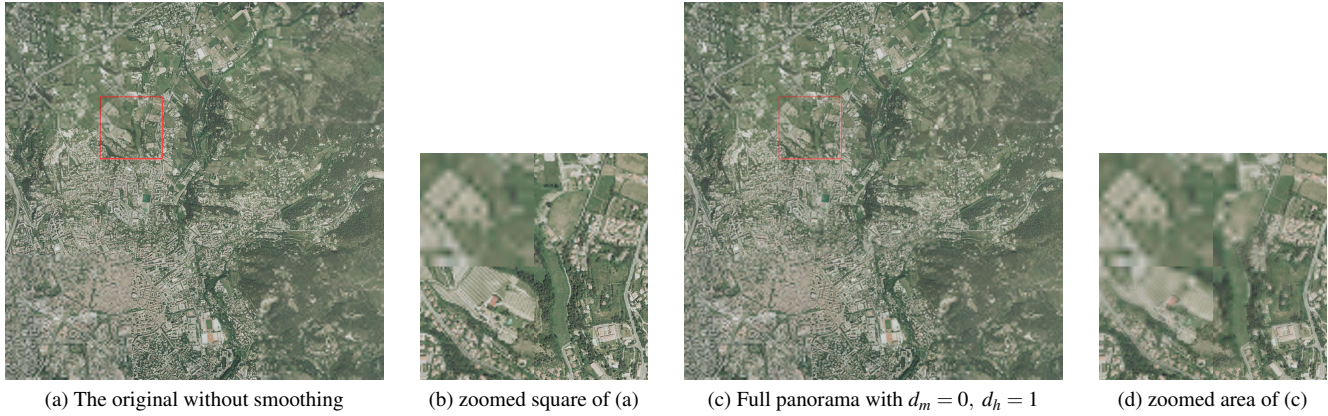


Figure 3: Example Texture Tessellation: $l_h = 0, l_m = 2, l_l = 4$

Input: width(w) of a DWT domain square subband
Output: Radial smoothing square mask of width w

```

1 BEGIN
2  $\delta \leftarrow w/2;$ 
3  $interval \leftarrow 2/w;$ 
4  $w \leftarrow w/2;$ 
5 for  $i = w * h - 1$  to 0 do
6   if  $i \geq w * (w - \delta/2)$  then
7     if  $i \% w \geq (w - \delta/2)$  then
8        $temp[i] \leftarrow 1.0;$ 
9     else
10       $temp[i] \leftarrow temp[i + 1] - interval;$ 
11    end
12  else
13     $temp[i] \leftarrow temp[i + w] - interval;$ 
14  end
15 end
16  $w \leftarrow w * 2;$ 
17 for  $i = 0$  to  $w * w/2$  do
18   if  $i \% w < w/2$  then
19      $B[i] \leftarrow temp[i \% \lfloor w/2 \rfloor + \lfloor i/w \rfloor * \lfloor w/2 \rfloor];$ 
20   else
21      $B[i] \leftarrow B[i - (2 * (\lfloor i/w \rfloor) + 1)];$ 
22   end
23    $B[w * w - 1 - i] \leftarrow B[i];$ 
24 end
25 return  $B;$ 
26 END

```

Algorithm 2: Radial Smoothing Function

we are going for the worst case for the corners by rendering level-4 approximate tiles which would mean a rendering with only 0.4% of the coefficients. For the centre we are taking highest possible quality, i.e. level-0. The 4-neighbors of center have the middle quality of level-2 approximation. The high quality gap between the three qualities is likely to make the tile boundaries conspicuous. A texture tessellation with these tiles without any smoothing treatment is shown in Fig. 3.a. The boundaries are not that visible due to the fact that the space we are using to render a large image of 3072×3072 pixels is too small. For this purpose we have magnified a small area (corresponding to the small square in Fig. 3.a) from the tessellation in Fig. 3.b. We have deliberately selected a region that contains each of the resolution

and smooth quality. This magnification is only for a comparison and the magnified portion does not represent the visual effect we are upto since the distance it represents warrants improved qualities at corners in our strategy. We will not be showing the whole tessellation for the treated examples but rather displaying the corresponding square region in each tessellation for comparison. Let d implies that $3d + 1$ lowest subbands have been avoided during smoothing, e.g. $d = 1$ implies that the lowest 4 subbands have not been touched. Based on d we are defining d_h which corresponds to the center tile and d_m that corresponds to the 4-neighbors. Note that since the 4-neighbors are level-2 approximates, the highest six subbands are already zero. This implies that d_m cannot exceed 1. If we do not tamper the lowest four subbands during the horizontal smoothing of E/W and vertical smoothing of N/W then $d_m = 1$, otherwise $d_m = 0$ where the only lowest level-4 subband is avoided from smoothing. d_h , which corresponds to the center O, can assume a value of up to 3 and it was observed that the border between the four tiles gradually smoothen as we decrease the value of d_h since more and more subbands are being involved in the radial smoothing of O. Since we are working on a worst case scenario and we are closer than we should be, the borders do not disappear at all but in the original environment the transition is seamless. Due to space constraint we are showing only one example smoothing in Fig. 3.c, where $d_l = 0$ and $d_h = 1$. Its magnified part corresponding to Fig. 3.b is illustrated in Fig. 3.d. From the latter, it can be observed that the border between the four tiles is far more smoother than the original.

Along the same lines the DEM can also be treated but the example at our disposal has a 96×96 DEM for a panorama of 3072×3072 which we believe is too small to be efficiently decomposed. It would have been interesting to take into account a larger DEM but due to circumstances beyond our control we were compelled to use a smaller DEM. Nowadays the DEM resolutions are approaching those of textures and hence for such DEMs one can safely apply the smoothing. A 3D visualization realized from a subset portion, at a particular angle, of the original example and one of the smoothed version, with $d_l = 0$ and $d_h = 1$, are illustrated in Fig. 4. A 3D view with the original can be seen in Fig. 4.a., marked by red ovals for the sake of comparison. Fig. 4.b shows the 3D view of our smoothed example and a comparison of the areas inside the red ovals with those in Fig. 4.a. suggests that the borders between the tiles are more diluted in the former case.



(a) No smoothing



(b) Smoothing: $d_m = 1$, $d_h = 3$

Figure 4: A 3D view corresponding to Fig. 3.

5. CONCLUSION

The results have been interesting in the face of the fact that we presented a worst case example tessellation in terms of quality difference as well as DEM size. The question arises that if the DEM is different enough to warrant its own LOD, how can one synchronize it? The answer to this is the fact that since the LOD is wavelet driven, one can always synchronously unify the DEM texture pairs as explained in [2] or even adapt the synchronization [17] to exclude some subbands from embedding. In the continuation of our work we would like to add some other techniques to our strategy, the foremost being mosaicking. We believe that if we mix up our smoothing strategy with DWT domain blending of subbands in adjacent heterogeneous tiles, the smoothing must be improved further. Second in line may well be some more sophisticated function instead of the linear one that have a better conformance to the DWT process computation between multiple coefficients.

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