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# Patch-based Terrain Synthesis

Leandro Cruz<sup>1</sup>, Luiz Velho<sup>2</sup>, Eric Galin<sup>3</sup>, Adrien Peytavie<sup>3</sup> and Eric Guerin<sup>3</sup>

<sup>1</sup>*VISGRAF Lab, Instituto de Matematica Pura e Aplicada, Rio de Janeiro, Brazil*

<sup>2</sup>*VISGRAF Lab, Instituto de Matematica Pura e Aplicada, Rio De Janeiro, Brazil*

<sup>3</sup>*CNRS - LIRIS, Université de Lyon, Lyon, France*

{lcruz, lvelho}@impa.br, {eric.galin, adrien.peytavie, eric.guerin}@liris.cnrs.fr

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Abstract: In this paper, we present an intuitive and controllable patch-based technique for terrain synthesis. Our method is based on classical patch-based texture synthesis approaches. It generates a new terrain model by combining patches extracted from a given set of exemplars, providing a control performed by a low frequency guide, a categorization of exemplars, and a map for distributing these categories. Furthermore, we propose criteria to validate the input, some structures to accelerate the patch choice, and a metric based on the process, these structures, and some specificities of the data.

## 1 INTRODUCTION

The creation of virtual terrain is a widely studied topic in computer graphics, because the large number of possible applications. Despite this topic has been studied for almost four decades, there is no definitive solution that creates a complex model, with many different features, according to nature, and controlled in a reasonably intuitive way.

In this paper, we introduce a method that contributes for achieving those goals. Despite our approach has not been tested on the generation of an entire and complex planet from an intuitive specification, we are contributing with all those goals.

The creation of an entire planet involves many research topics. We are focused on terrain synthesis. There are more than one way to represent a terrain, we use a regular Digital Elevation Model (DEM): a matrix whereof each value represents the respective height of the terrain. A complete survey for landscape creation, and terrain representation and synthesis was presented by (Smelik et al., 2014).

There is a seemingly trivial association between the DEM and a grayscale image. So, we adapt a classical approach for image synthesis to the context of terrain generation. Our method is based on the gluing of patches extracted from real exemplars. The choice of a patch-based technique allows to keep some landform features present in real data (and so, present on nature). Furthermore, for creation of huge model this larger unit (in comparison to a pixel) of the data synthesized in each step accelerates the creation process.

Applying directly Image Quilting method to generate a terrain does not produce realistic results as shown in Figure 2. The generated terrain model is not as good as the texture. The overlapped patches are not well fitted and the global topographic features (such as mountains and valleys) have a non natural distribution. It is because the terrain exemplar is a non-stationary model, and so, it does not have information enough to create a good terrain. Thus, our patch-based approach aims to deal with the specificities of terrains to obtain better results.

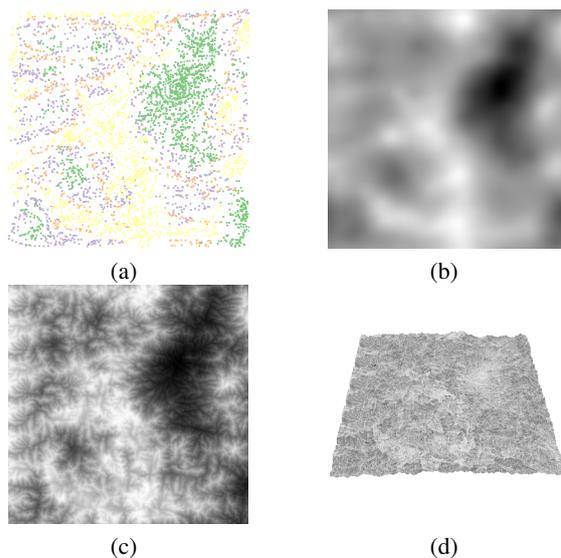


Figure 1: The specification (a) and generated guide (b); and the synthesized DEM model (c) and its 3D view (d)

We provide an intuitive way to control the synthesis, based on a guide, containing the coarse features of the target model, and a map which associates parts of the target with categories of the exemplars. Besides the controlled behavior, our patch choice is based on constraints derived from natural features, and some structures to accelerate this process. Figure 1 shows an example of a guided terrain modeling.

The main contributions of this work are:

- The creation and use of a guide, with the coarse structures of the target, for synthesis control;
- An exemplar categorization and a map for associating regions of the target with these classes;
- A criterion for validation of the exemplars according to the guide, and a rule for choosing a minimum set of exemplars, into a large data set of exemplars, able to cover the guide;
- An adaptation of the classical patch-based algorithm including, besides of control, a new optimization structure for patch choice, and a new patch insertion approach (both based on the geometric nature of the data)

In this paper, we will present, in Section 2, some works related to terrain synthesis, emphasizing the patch-based approaches. In Section 3, we will introduce our controlled patch-based technique for terrain synthesis, explaining the creation and use of control structures, introducing a new metric for patch choice, a new patch insertion approach. The input validation, and exemplar selection will be present in Section 4. Finally, in Section 5, we will present some conclusions and future works.

## 2 RELATED WORKS

Terrain synthesis is a widely studied problem in computer graphics. It began by the use of procedural approaches (Musgrave et al., 1989). But, the recent researches are based on simulation of natural phenomena (Genevaux et al., 2013), or on composition of structures taken on real data (Zhou et al., 2007).

There are many pixel-based methods for texture synthesis that can be used for terrain synthesis (Lefebvre and Hoppe, 2005). But, in general, they are concerned to create a big homogeneous model with the features contained in a provided exemplar.

(Han et al., 2008) proposed a pixel-based approach using a graph of exemplars in multiscale. This new structure allows the synthesis to create an heterogeneous model, and possibly with an infinity resolution. (Cruz et al., 2013) adapted this approach for terrain synthesis.

## Patch-Based Approaches

Patch-based synthesis methods (Efros and Freeman, 2001) create a model by covering the target using patches taken from a given exemplar, placing them with some predefined overlapping over the already synthesized parts of model. The choice of which patch will be chosen depends on some metric based on comparison of the overlapping regions and, eventually, comparing some features of a control model. After the choice of which patch will be inserted, a cut is calculated, into the overlapping region, separating the old part and the new one. Our synthesis approach is similar, but it includes a more sophisticated control and some adaptation based on the nature of the data.

An extension of the Image Quilting (Efros and Freeman, 2001), presented by (Lasram and Lefebvre, 2012), performs the insertion of a set of patches in parallel. The authors introduced an iterative method whose, in each step, it is necessary to choose a patch for each cell of the grid, define the cut and insert it in the case when there is an improvement of the synthesis quality (based on a specific metric). Our synthesis approach is sequential. But, it is seemingly easy to extend that method to use our control and patch choice and insertion approaches.

(Zhou et al., 2007) proposed a patch-based method for terrain synthesis, creating the new model by gluing patches taken from an exemplar. They also provide a map with the main desired ridges or valleys for controlling the synthesis. During the synthesis, the patches are chosen by matching of a descriptor based on these features. This control approach is based on features in an intermediate scale. Our main concern is to control features in a higher scale. Although, it is possible to add their feature map in our synthesis improving the control.

(Freeman et al., 2002) proposed a super-resolution approach for image synthesis. This approach chooses the patches by comparing a low frequency on a base image (like our guide) and it matches the high frequency in an overlapping region. Our approach is similar, improving the control and the patch choice and insertion.

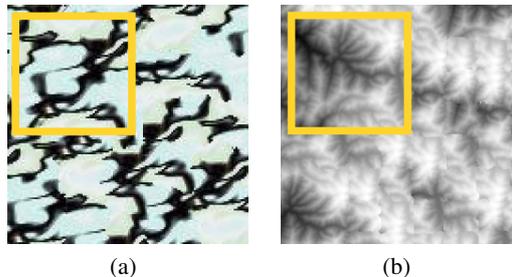


Figure 2: These results were generated using the exemplar shown in yellow square through the Image Quilting method.

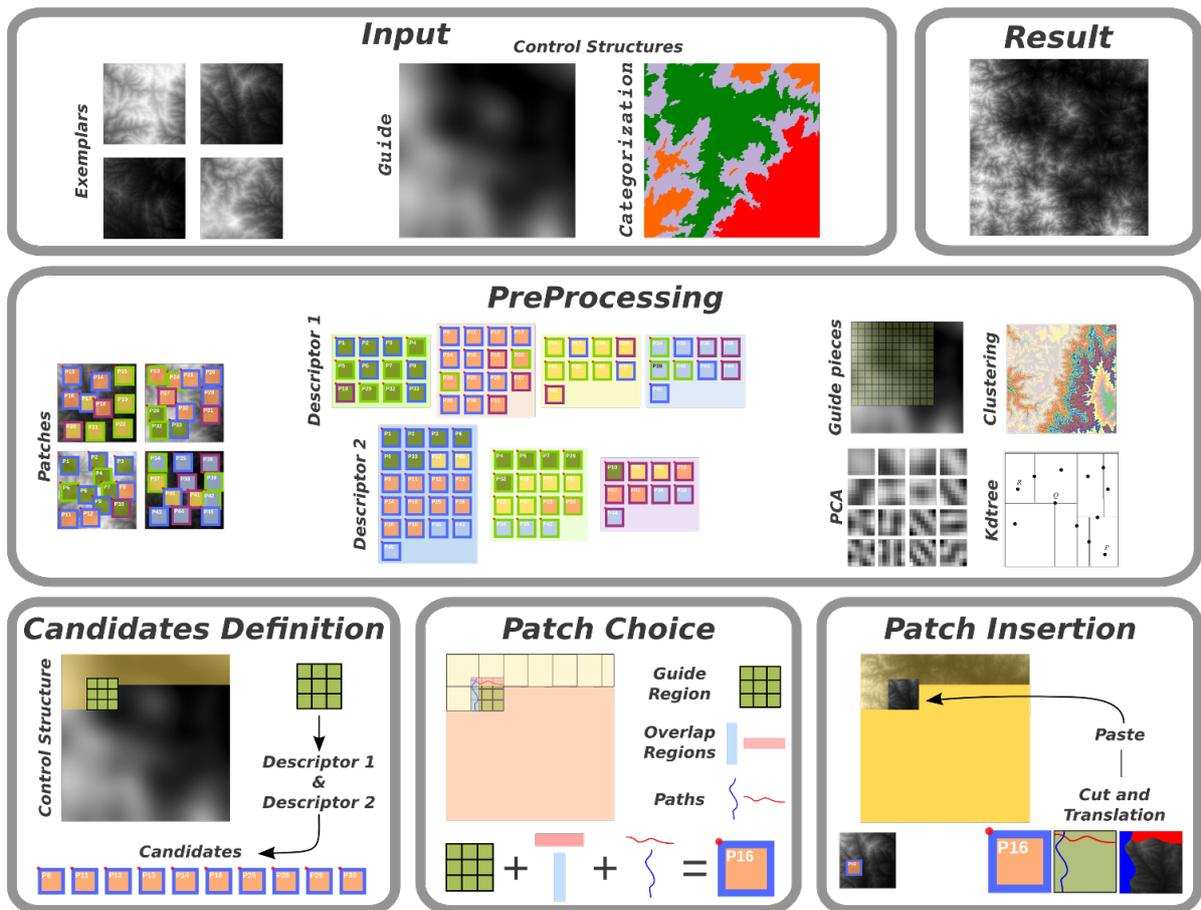


Figure 3: The method begins by the input definition: exemplars, and control structures. Following, in the synthesis step, we choose a patch for each part of the grid. The result is a terrain model, with the predefined size and features.

### 3 PATCH-BASED TERRAIN SYNTHESIS

The synthesis process is based on a sequential choice and insertion of patches. Figure 3 shows the pipeline of our method. The essence of the synthesis method is the creation of a grid of overlapped regions, onto the target area, and for each part of this grid to find a patch well fitted to the pre-synthesized parts. This search is performed by analyzing each possible patch of the exemplars, based on some rules.

We will present a patch-based technique for terrain synthesis. The input of our method is a set of exemplars and the control models. The first control model is the guide: a DEM, with the same resolution of the target model, containing the desired low frequency. The second one, is the categorization map: an image splitted in some regions, and associating each region with a class of exemplars (the exemplars are pre-categorized according to some feature). We will talk about control structures in Subsection 3.1.

The synthesis begins by the definition of which patches are candidates to be inserted in the current part. It is a subset of all possible patches, such that, they are compatible to the respective region of the target (relative to some rule). The rules for candidates definition will be discussed in Subsection 3.2. The initial candidates set has a large number of possible patches, chosen with high level criteria. These criteria aim to match the coarse features of the patches and the control structures. They are able to choose the candidates by a low cost comparison.

After having applied these high level criteria, we have to choose the patches that have a good matching on the overlapping regions. We achieve it using low level criteria, i.e. rules for performing a more detailed comparison. Furthermore, it is necessary to define the cut to split the pre-synthesized part of the part came from the chosen patch. These steps will be present in Subsection 3.3.

We will also talk about, in Subsection 3.3, the classical cutting and pasting approach for patch insertion, and the blending into the overlapping region to

remove seam discontinuities, applied after the patch insertion. Furthermore, because we know that our data is a terrain, we can perform some small vertical translation on the patches, to improve the matching, before the insertion. We will present this approach on Subsection 3.4.

Finally, in Subsection 3.5 we will talk about the processing optimizations. We will describe the acceleration structures, created in the preprocessing step, and how they optimize the patch choice.

### 3.1 Control

The guide is a very important structure for control. It contains the macro structures desired for the model, e.g. where there are mountains, canyons, big plateaus, etc. It also contains an implicit categorization of the exemplars, since it has a wide range of height, and so each exemplars, in general, can be only used in some parts of the model. Also, it is a continuous model, and so it helps the method to guarantee a continuous synthesis. Furthermore, it guarantees that the patch choice respects a coherent flow of the data.

We can create the guide by filtering an existing terrain model (when we want the same macro features, but with different details). Another possibility is to use sketches to specify the macro structures (Tasse et al., 2014). Another possibility is to use some kind of brushes or seeds based on features extracted from the exemplars. Figure 1 shows an example of a guide created from a set of seeds related to four different classes of heights.

The map of categories can be based on a subdivision of the guide by clustering of heights. The clustering process creates a set of regions associated to the respective class. This map can be created by setting which regions will be associated with each category of exemplars. Of course, this association must be enough to cover the entire target model, and must have intersection to be able to synthesize the transition areas. Furthermore, in the association of regions and categories we can relate regions of same height to different categories, and we can relate a category to more than one level of heights (since the exemplars have the entire range of heights). Figure 4 shows an example of map created with these features.



Figure 4: The categorization map

### 3.2 Candidates Definition

In general, in this kind of approach, we find the best patch by comparison of the overlapped region of the pre-synthesized part and of each possible patch from exemplars. However, depending on the amount of input data, the brute force strategy is prohibitive.

The initialization of candidates uses high level criteria, whereof we can take some decision that discards a big amount of data by a low cost. And, we can use more than one acceleration structure, like a chain of processing, by removal of patches from the candidates set. After that, to obtain a good patch matching, we have to satisfy more specific constraints.

The acceleration structures are created based on some descriptor  $D$  that represents a patch by a tuple of  $k$  numbers (where  $k$  is much smaller than the patch size). These structures are Hash Tables  $H$  whose keys are  $k$ -tuples obtained by clustering the representation of the patches given by  $D$ .

We have a descriptor  $D_i$ , and the respective  $H_i$ , for each control structure. During the synthesis, the region being synthesized is also represented by  $D_i$  and it is compared to the keys of  $H_i$  to determine which clusters are closer (possibly more than one). Hence, we obtain the candidates resembling to the control, according to the feature described by  $D_i$ , without analysing individually all possible patches.

The first criterion for candidates definition is the categorization. Its descriptor is the exemplar categorization. It can be done by a user, or using some other exemplar descriptor. We associate each category to a number, and so, during the synthesis we will only consider the patches on exemplars which the class is contained in the respective region on the map. This criterion selects a big amount of candidates. Thus, we are also chaining other rules more constrained.

The second criterion is based on the low resolution structures. We can compare the average height of the guide region and the one of the patch, but it is a poor comparison, inasmuch as extremely different distributions of heights can have the same average. To improve the comparison, we divide this region in a block of  $N \times N$  pieces, and we compare the average of each piece. These pieces are created using a box filter, and we opt for  $N = 3$ . In our tests, bigger values for  $N$  have caused overconstrained matching.

Another structure is related to a more compact description of the overlapping regions. We tested the clustering using the PCA representation (described on Subsection 3.5) and the height average. The PCA is a global representation, while the blocks represent better local features. Because of this, the second approach provided a better cut definition.

### 3.3 Patch Choice and Insertion

The candidates are patches well globally fitted to the desired macro structures, chosen according to the control structures. But we also have to guarantee that micro structures are also being well matched. For this purpose, we will use low level criteria (and thus more expensive tests).

This choice is achieved by comparison of the patch with the guide region related to the part is being synthesized  $G$  (using euclidean distance), the overlapping region matching  $O$ , and the cost of the cut  $P$ . It is performed by a solution of an optimization problem based on the following the energy function  $M$ :

$$M(p, c) = \alpha G(p, c) + \beta O(p, c) + \gamma P(p, c) \quad (1)$$

where  $\alpha$ ,  $\beta$  and  $\gamma$  are given parameters.

If the overlapping region matching is close enough (big *beta*) we can use a greedy algorithm to calculate the path (Efros and Freeman, 2001). This solution create a path by local decision. So, it is not necessary the global best cut. In general, the priority for the overlapping matching can harm the guide fitting. So, we prefer to use a better path creation approach, based on Dynamic Programming (Lasram and Lefebvre, 2012). It is more expensive, but it allows us prioritize the global feature matching.

The classical approach for patch insertion consists in cutting it and paste the respective area (Efros and Freeman, 2001). Nevertheless, we can apply a blending of the transition area using Poisson Blending (Zhou et al., 2007) or using a smooth interpolation. In both cases the calculation of the path can be avoided.

But, to guarantee a good matching, and so a good insertion, we can apply a vertical translation of the patch, and so add this translation to the patch before inserting it. The calculation of the optimal translation will be explained in the next subsection.

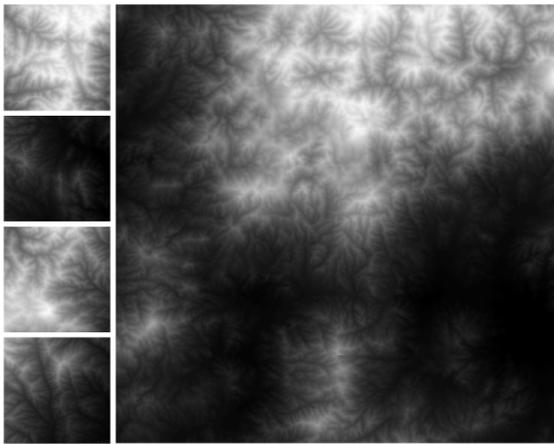


Figure 5: A terrain synthesized using our approach

### 3.4 Vertical Translation

Some works apply a patch deformation to improve the matching (Lasram and Lefebvre, 2012). However, we avoided this kind of deformation because it could create unnatural artifacts (unnatural in the sense: forms which are impossible to exist in the nature).

However, we can take advantage of the geometric nature of the data and apply some rigid transformation into the patch to reduce the seam error. The patch representation is a descriptor invariant to translations in the domain. Furthermore, we compare the region in the target with all similar candidates in the exemplar, and so all possible translations of the patch over the target have been implicitly performed. Moreover, we can perform a translation in the *height* direction.

So, let  $p$  the position in the target where we will insert the patch, and  $c$  the patch candidate. The best height translation can be achieved by solving the following optimization problem:

$$\bar{h} = \min_{h \in \mathbb{R}} \|B(T, p) - V(B(E, c), h)\|^2 \quad (2)$$

where  $B(A, x)$  is the function which returns the block (with a predefined size) of  $A$  originated in the position  $x$ , and  $V(A, h)$  the height translation of all points of the DEM (or the block)  $A$  by the scalar  $h$ . The solution of the optimization problem is:

$$\bar{h} = \frac{1}{nm} \sum_{i=0}^n \sum_{j=0}^m (B(T, p)_{i,j} - B(E, c)_{i,j}) \quad (3)$$

Another advantage of the vertical translation is that we can create a model whose the height range is bigger than the input one. Of course, it is not interesting to increase a lot this range, because some natural phenomena depends on the height. But, small translations are not in contradiction to nature. The candidates selection by comparison with the guide guarantees that the translation of the chosen patch is small, but if  $|h| > \lambda$  (for a given small  $\lambda > 0$ ) the translation will be not considered.

### 3.5 Processing Optimization

All acceleration structures are created in the preprocessing stage. We perform the clustering using the  $k$ -means algorithm. The choice of  $k$  aims to avoid small clusters, otherwise we could have small candidate sets (and then, an inefficient patch choice).

Another optimization regards the overlapping region comparison. We reduce their dimension by use of Principal Component Analysis - PCA (Lefebvre and Hoppe, 2005), and find the best matching by the

Nearest Neighbor method (Freeman et al., 2002). The PCA basis and kd-tree used in the second method is also created in the preprocessing stage.

Finally, in the optimization performed in the patch choice step, the most expensive calculation refers to the path creation. So, we can solve this problem in two steps. The first one keeps the candidates close to the optimal one defined by  $G$  and  $O$ . And, the second step calculates the path for all remainder candidates and pick the best.

## 4 Input

The quality of the synthesis depends on the choice of the exemplars. If the amount of the data is too small there is not enough information to perform an adequate synthesis. However, a huge amount of redundant data increases significantly the processing cost.

In general, in texture synthesis work, the user provides the exemplars. In our approach, it is extremely important that the exemplars be able to cover the guide. So, to avoid many trial and errors, we perform an input validation. It is performed by checking if all blocks in the guide are related to a minimum amount of patches from exemplars. In general, we ask for this minimum be greater than 500 candidates, to have many alternatives for the next criteria.

In cases where the synthesis is performed without a guide, we have to guarantee that the exemplars are compatible: i.e. all exemplars have an enough amount of patches in the same range of height of patches in other exemplars. It is necessary that the synthesis uses patches from all exemplars without big discontinuities. When we use a guide, an adequate coverage has this validation implicitly. The compatibility of patches is also performed by the comparison of blocks of piece (analogous to the comparison with the guide).

Furthermore, we cluster the patches from exemplars according to the blocks of average of pieces, and create the categorization according to this clustering. From this division, the user can create the categorization map.

## 5 CONCLUSION

We introduced a patch-based approach for terrain synthesis. The focus of our approach is the synthesis control. Even it has been proposed a control of structures, a future work for this research is the improvement of the creation and use of these elements. We can include the Ridges and Valleys control (as in

(Zhou et al., 2007)), and improve the coarse structures creation for the guide.

Another possible guide creation approach is based on hydrology. The user can place vectors related to water flow. Thus, we can fill the entire area, by interpolating them. Mathematically, the flow is the gradient of the DEM. So, we can integrate them for generating the guide.

Despite of the advances for terrain synthesis, there is a lack of high level methods for complex models creation, and methods that combines different kinds of nature elements. The main future work for this research is to pursuit these goals.

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