

# Towards the Creation of Digital Stones from 2D Samples

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## Abstract

*In order to decide which preservation strategies one should follow for Cultural Heritage objects made of stone, it is necessary to estimate the impact of different alternative strategies. A useful aid in such a process is the simulation of the stone degradation process. The first step in such a process is to create realistic digital representations of stones. In this work we present early efforts to create 3D voxelized representations of stones from given 2D example-textures of the desired stone-material. The process aims at the creation of 3D stone materials, consistent with 2D samples. The presented work is one part of the PRESIOUS EU project.*

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations

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## 1. Introduction

Stone degradation is taking place over a long period of time and impacts Cultural Heritage objects made of stone over the centuries. In order to protect these Cultural Heritage objects in an appropriate way, an improved estimation of the natural decay is of importance as it helps to select effective protection methods. In this work we describe the first step in the simulation process of the stone degeneration. This is to create a realistic digital representation of the stone that fits to given measurements. In particular, we consider the case where sparse measurements of the stone material are available on the surface or more general in the interior of a particular stone sample. In order to achieve this we exploit and extend existing texture synthesis methods and integrate them into a multi-seed priority filling procedure within a voxelized structure. To verify this concept we take a 2D texture of stone-material and fill in a volume that is bounded by a geometric mesh. Providing some initial data-values at given points, the cross sections of the created volume show that the method results in stone data that fit to a given or measured stone sample.

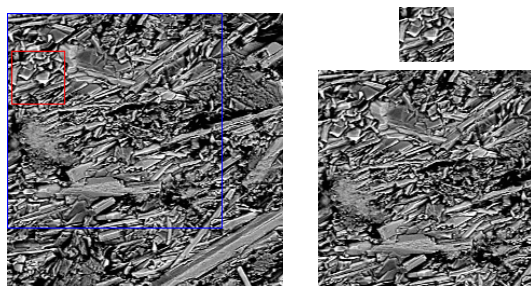
### 1.1. Related Work

Only very few publications are available which are directly concerned with the simulation of stone decay processes. The most related one is from Julie Dorsey et al. [DEJ\*99]. They developed an interesting approach to model and render

changes in the shape and appearance of stone. Recognizing that the complex erosion processes change the stone mainly at the surface, they introduced a *slab* structure that covers the narrow region around the stone surface that is created interactively. This volumetric boundary band represents the domain for their simulation of chemical weathering processes. However, they did not focus on the stone structure itself and made just use of some standard solid 3D procedural textures to create synthetic stone data. For example they exploit Perlin's turbulence function [Per85] to obtain structures looking like marble or imitated granite is by cellular texturing similar to Worley's method [Wor96]. In contrast, our aim here is to rebuild stone materials from given example textures incorporating sparse local measurements that are available. In later stages this will allow us to come statistically closer to a real chemical and physical modeling of the stone.

## 2. Approach

The here presented approach to synthesize volumetric stone textures is build upon a non-parametric sampling method that can be related to Markov Random Field (MRF) models for 2D texture generation. In section 3 we first describe the idea of the 2D sampling methods and extend these to 3D in section 4. The texture pattern we use for the illustration of our approach is an electron microscopy image (cf. figure 1) of a stone-surface of a soapstone from the Nidaros cathedral located in Trondheim, Norway.



**Figure 1:** *Left:* Electron microscopy image ( $256 \times 256$  pixels) of a soapstone from the Nidaros cathedral. The full texture corresponds to an area of approximately  $0.2\text{mm} \times 0.2\text{mm}$ . *Right:* The  $50 \times 50$  and  $200 \times 200$  pixel wide sub-areas from the electron microscopy image which are used to illustrate the influence of the training patch size in a non-parametric sampling approach (cf. figure 2).

### 3. Markov Random Field Sampling

A promising texture synthesis approach can be found within the field of statistical image analysis. The basic idea is to model the texture as a Markov Random Field (MRF) and use Gibbs sampling for the synthesis. Within this model a texture is interpreted as a local and stationary random process. However, an explicit probability function has to be modeled. Then, sampling from this distribution results in a synthesized version of the texture. For details describing the theoretical and also applied aspects of Markov Random Fields we refer to the book of G. Winkler [Win06]. Unfortunately, this approach is known to be computationally expensive. Therefore, current successful approaches resort to algorithms known as non-parametric sampling approaches, which were introduced by Efros and Leung [EL99] in 1999.

#### 3.0.1. Efros & Leung's Algorithm

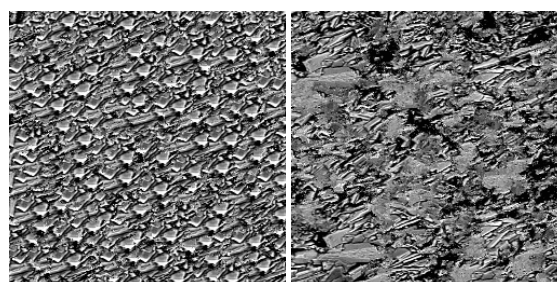
The main idea of the non-parametric sampling from Efros and Leung [EL99] is to use a single example texture as a statistical model for MRF sampling. This allows to synthesize new texture samples from a given texture example. The main assumption is that the present example is large enough to capture the (statistical) properties of the texture, even if the given sample is only a single draw out of an (nearly) infinite number of possible samples. The synthesized texture is grown by sampling from the approximate conditional probability distribution, that depends on the actual neighborhood of the pixel-position one is about to sample:

$$P(x_{i,j}|N(x_{i,j}))$$

Here  $N(x_{i,j})$  denotes the neighborhood of the pixel  $x_{i,j}$  and  $P(x_{i,j}|N(x_{i,j}))$  refers to the conditional probability distribution for the gray-values at location  $(i, j)$  when its neighborhood is determined. This model represents a Markov random

field when the conditional probability depends only on the local neighborhood of the considered pixel at  $(i, j)$ .

In its basic version the texture is synthesized starting from a seed pixel and then grown outwards. For the pixel  $x_{i,j}$  that will be synthesized, an approximation to the conditional probability  $P(x_{i,j}|N(x_{i,j}))$  is obtained by weighting the candidates that fit best to the neighborhood  $N(x_{i,j})$  of already synthesized pixels in the input texture. Extensions to a multiresolution synthesis pyramid and a fixed neighborhood [WL01] lead to computationally more effective variations and improvements of the approach. Exploiting a reference implementation by Paget [Pag99] we illustrate the capability of synthesizing a 2D stone pattern from a small  $50 \times 50$  training patch in figure 2 (the image on the left hand side). The used small training patch can be seen in figure 1 (top right). Visually the 2D approach captures the charac-



**Figure 2:** *Non-parametric sampling approach. Left:* A synthesized  $256 \times 256$  pixel large texture region using a small  $50 \times 50$  stone texture example. *Right:* A synthesized  $256 \times 256$  pixel large texture region using a larger  $200 \times 200$  stone texture example.

teristics of the training texture very well. In addition, with increasing neighborhood and training texture size, the long range characteristics – present in the electron microscopy image – become also apparent as can be observed on the right side of figure 2. It shows the synthesized texture using a  $200 \times 200$  training patch that is depicted on the bottom right side of figure 1.

### 4. Sampling 3D Stones

As stone degeneration is a volumetric process, the 2D behavior of the non-parametric sampling approaches encouraged the development of a prototypical implementation of a new approach that allows the sampling of voxels within a 3D volumetric structure based on 2D texture examples. Starting from sparse surface measurements of the stone texture, we found that our stone texture filling procedure has to fulfill the following requirements:

- Reproduce the exact texture values at sparsely given locations or areas. (Note that we allow for sparse measurements inside the volume too, as sparse surface measurements represent a special case of this.)

- Synthesize the 3D texture in undetermined areas such that it is similar to a provided sample texture.

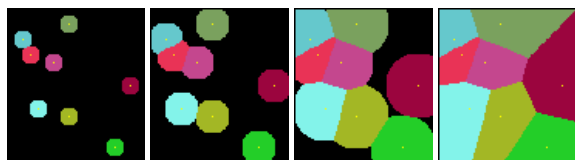
Below we explain the key ideas of the algorithm that we developed.

#### 4.1. 3D Stone Texture from 2D Examples

In this section we describe our approach to extend the basic idea of non-parametric sampling for 2D textures to the sampling of 3D stone textures with sparse texture constraints. One presumption we make is that at large scale the considered stones are in general amorphous and exhibit homogeneous and isotropic behaviour. In other words, in our approach we did not consider any direction or orientation within the stone as preferred. For crystals this would likely not be the case, but for soapstone and marble, present at the Cultural Heritage site we are mainly concerned with (i.e. Nidaros and Elefsis), this is a reasonable first approximation.

##### 4.1.1. Voronoi Cell Structure

One of the observations we exploit within our method is the fact that a flood-fill procedure which starts simultaneously at different labeled seed-points and grows radially outwards from these points, will automatically result in a Voronoi cell structure. Thus, one Voronoi cell is created for each seed point. This behavior is illustrated in 2D in figure 3, and is similar for higher dimensions. The flood-fill algorithm can easily be implemented with the help of a priority queue, and the available area is filled by starting simultaneously from the several given seed points.



**Figure 3:** Progress of a 2D priority flood-fill procedure is shown. Starting from several seed-points it automatically results in a Voronoi-cell structure. One Voronoi cell is created for each seed point.

##### 4.1.2. Filling of Volumetric Structures

We exploit the previously described filling procedure within our 3D approach to generate the internal (volumetric) stone structure. The given and sparsely distributed measurements at the seed points serve as constraints for the material that is present at certain locations. The texture must be created when the flood-fill procedure extends the seed areas radially. Therefore, an inner step of the flood-fill algorithm is that we have to synthesize a new stone voxel. A simple way of doing this would be to sample from the histogram distribution of the stone example texture but the resulting pattern can not

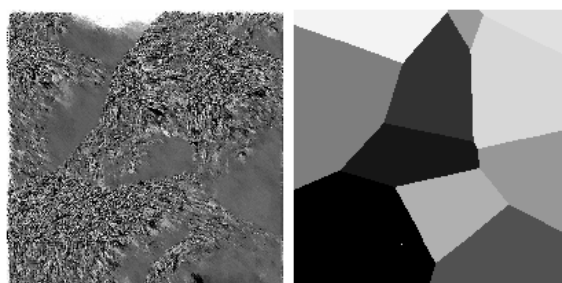
exhibit any longer range characteristics that are present in a texture. In order to incorporate and take into account the neighborhood we can adopt the idea of non-parametric sampling for voxels, which is explained in the next section.

##### 4.1.3. Non-Parametric Sampling Applied in 3D

Within the priority flood-fill procedure (leading to a radial growing), a single voxel is added and has to be filled with a new scalar value, that represents the stone material. Note that the scalar value can be substituted by vector values to consider the chemical composition of the stone material. The new voxel, along with its already sampled and present neighborhood, should fit to a provided 2D example texture of a stone. For this we can directly employ the 2D non-parametric sampling approach also for the 3D case, when we (randomly) select an orientation that determines the already sampled voxels in a plane neighborhood around the voxel. The extracted 2D neighborhood patch is used in the basic 2D non-parametric sampling process, which determines the gray-value that is assigned to the voxel. Note that the non-parametric sampling can be performed as described above by finding a collection of suitable gray-value candidates that have a similar neighborhood as the extracted 2D patch and then subsequently sample from these candidates. Randomly changing the orientation of the considered neighborhood plane, when the flood-fill progresses, has the aim to create a consistent texture appearance in an arbitrary direction.

##### 4.1.4. Preliminary Results

We prototyped the above sketched idea and show our first results in figure 4. It depicts a representative plane slice



**Figure 4:** Slice through a cubic volume that is being filled with stone material. For comparison the corresponding Voronoi cell structure is shown in the image on the right hand side. One can observe that the non-parametric sampling approach starts to exhibit longer range patterns in 3D.

through a cubic 3D volume filled with stone material from 19 seeds. The volumetric texture is computed by a non-parametric sampling considering neighbors within a  $5 \times 5$  neighborhood. One can see that it already exhibit longer range patterns in 3D. For illustration purposes the corresponding Voronoi cells are shown in the image on the right



**Figure 5:** A 3D volume obtained by the voxelization of the "Armadillo" mesh, which is subsequently flood-filled starting from several seed points. Three cross-sections of this volume are depicted in figure 6 and reveal that the considered  $5 \times 5$  neighborhood in the sampling is large enough to make the Voronoi cell transitions less apparent.

hand side of figure 4. There 11 out of the 19 Voronoi cells are visible. Figure 5 shows the result when we flood fill the interior of the "Armadillo" mesh (Source: Stanford University Computer Graphics Laboratory) with the described non-parametric sampling method. The corresponding texture slices are depicted in figure 6 and allow a visual inspection of the synthesized stone volume in three orientations. We observed that the longer range patterns are becoming clearer with an increasing size of the considered neighborhood and that the transition between the Voronoi cells becomes less apparent. The sampling from just the histogram distribution would result in a random uncorrelated distribution.



**Figure 6:** Three slices that go through a common point in the volume shown in figure 5 are depicted. We observe that the transition between the Voronoi cells becomes less apparent and that longer range stone patterns become clearer with increased considered neighborhood.

#### 4.2. Conclusions

Within this paper we presented an approach to synthesize volumetric stone data. Our focus here was to create a digital volumetric representation of a stone that has to be compatible with surface and/or volumetric measurements of the real

stone. We explored the idea by synthesizing textural data obtained from an electron microscopy image and we intent to extent the textural information with measured physical and chemical properties of particular stones. This will help and guide us to estimate the degradation of stone monuments in Cultural Heritage. Our initial experiments show promising and encouraging results that fulfill the basic requirements that we have for a usable stone builder. However, the presented work is at an early stage and several aspects have to be considered in future work. This includes in particular the assessment and suitability of the developed method on real stone-data along with performance measurements.

#### 4.3. Acknowledgments

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