Procedural 3D Asteroid Surface Detail Synthesis

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Abstract

We present a novel noise model to procedurally generate volumetric terrain on implicit surfaces. The main idea is to combine a novel Locally Controlled 3D Spot noise (LCSN) *for authoring the macro structures and 3D Gabor noise to add micro details. More specifically, a spatially-defined kernel formulation in combination with an impulse distribution enables the LCSN to generate arbitrary size craters and boulders, while the Gabor noise generates stochastic Gaussian details. The corresponding metaball positions in the underlying implicit surface preserve locality to avoid the globality of traditional procedural noise textures, which yields an essential feature that is often missing in procedural texture based terrain generators. Furthermore, different noise-based primitives are integrated through operators, i.e. blending, replacing, or warping into the complex volumetric terrain. The result is a completely implicit representation and, as such, has the advantage of compactness as well as flexible user control. We applied our method to generating high quality asteroid meshes with fine surface details.*

CCS Concepts
• *Computing methodologies* → *Volumetric models;*

1. Introduction

The evolving space technologies for planetary missions have grown from flyby observation to collect samples from celestial bodies. For instance, currently there are two ongoing sample return missions: NASA's OSIRIS-REx and JAXA's Hayabusa2 study the asteroids Bennu and Ryugu, respectively. To ensure the success of such asteroid sampling missions it is essential to test the missions in advance with a wide variety of diverse scenarios of the hardly known asteroid shapes and surfaces. This is typically done in virtual testbeds. Hence, highly detailed 3D models of asteroids shapes and surfaces are required to cover a wide variety of possible scenarios. Obviously, also the video game or movie industry are interested in complex and realistic high quality 3D models of celestial bodies. Generating them manually is not an option because of the large amount of test cases. Consequently, automatic shape generation is required.

One promising technique to alleviate the challenge of authoring complex asteroid models is procedural content generation. Proceduralism refers to a method that abstracts the underlying shape to be represented into by compact, elegant rule or equation that can be amplified on demand to produce complex models.

We introduce a novel noise model that combines *local controlled spot noise* (LCSN) [PGDG16] with *Gabor noise by example* (GNBE) [GLLD12] to solve the challenge of automatic asteroid surface detail generation. Our main contributions are:

• a new spatial defined kernel formulation of spot noise relying on several intuitive parameters to generate arbitrary sized craters and boulders and
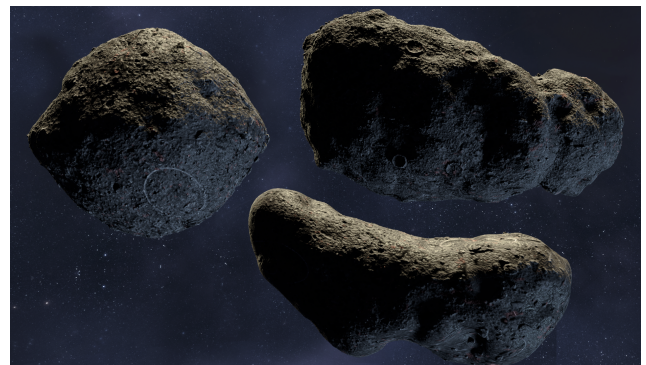

Figure 1: *Asteroid field. All asteroid models are generated with our volumetric terrain model.*

• an integration of GNBE with our 3D noise model which can extract noise parameters from example textures.

In order to generate a rough shape of the celestial bodies we have modified AstroGen [LWZ18] which is a volumetric modeler that can use existing geometric models as constraints to implicitly approximate the shape by a polydisperse sphere packing [WZ10]. Our method can be a supplement to the procedural workflow to generate diverse complex surface details of celestial bodies (Figure 1 present the possibilities offered by our new noise model to generate volumetric terrain through the rough shape of several asteroids).

2. Related Works

Procedural noise gained attention and interests of many researchers in the past decades due to its efficiency, low storage requirements and its non-periodicity. A detailed overview of procedural noise functions can be found in [LLC*10]. Here, we review more recent developments which are directly related to our work.

Galerne and Lagae [GLLD12] proposed *Gabor noise by example*, a segmentation approach of the exemplar Gaussian texture's power spectrum into a sparse sum of Gaussian envelops, to generate noise with a similar power spectrum. However, the Gaussian texture fails to preserve large structures which is very important in many applications. Several attempts have been made to deal with structured patterns as well as the efficiency of the algorithm. Gilet et al. [GSV*14] introduced *local-random phase* (LRP) noise that demonstrated great ability to generate noise textures with spatial and spectral control. Their noise function was defined on a regular grid to sum localized cosine functions with random or deterministic phases, and the local phases of the input texture can be preserved to generate structure patterns. Subsequently, Pavie et al. [PGDG16] proposed *Locally Controlled Spot Noise* as an extension of the LRP noise model that is based on a controlled density profile distribution of Gaussian kernels to generate near-regular to irregular patterns. More recently, Tricard et al. [TEZ*19] presented phasor noise which addressed the contrast oscillation problem and reformulates the Gabor noise into local density and phase, providing fine controls over the fine microstructures through editing the profile function. Cavalier et al. [CGG19] further strengthened LCSN by introducing an intuitive geometric matrix formulation to the kernel and an anisotropic filtering scheme which significantly improved the rendering result of procedural textures.

3. Our Approach

The basis of our implicit asteroid generation is a metaball representation defined by a sphere packing of the rough shape according to AstroGen [LWZ18]. Additionally, we add surface details via spot and Gabor noise. Hence, the complete asteroid can be represented as an isosurface of the function $S = \{ p \in \mathbb{R}^3 \mid f(p) = T \}$ with:

$$f(p) = m(p) + \sum_{i=1}^{I} dist(p - p_i) n_i(p) \tag{1}$$

where $m(p)$ represents the implicite surface of the metaballs for each point $p \in \mathbb{R}^3$ in 3D. Additionally, we assign a noise function n_i to each sphere $i = 1, ...I$ to control the influence of the individual spheres to the surface details. This guarantees the locality of our approach. Obviously, the influence also depends on the distance $dist(p - p_i)$ of the sphere's center p_i to the point p.

The noise functions for the surface details $n_i(p)$ are a multi-layer of spot and Gabor noise functions and can be written as

$$n_i(p) = \sum_{j=1}^{J} spot\_noise_j(p) + \sum_{q=1}^{Q} gabor\_noise_q(p) \tag{2}$$

In the following, we will concentrate on the surface details $n_i(p)$. We refer the interested reader to [LWZ18] to find more about the computation of the metaballs shape $m(p)$.

3.1. Macro terrain structure

The LCSN model is a kind of sparse convolution noise introduced by Pavie et al. [PGDG16]. It relies on the summation of spatial kernels at uniform positions in texture space and the structural feature of the spatial kernel can be transferred to the texture. In order to generate two different types of craters we introduce two spatial kernels (see Eq. 4 and 5) as well as new control parameters for the synthesis of various shapes of craters:

$$spot\_noise_j(p) = \sum_{l=1}^{L} w_l(k_1(p - p_l) + k_2(p - p_l)) \tag{3}$$

with the two different kernels

$$k_1(p) = e^{-\alpha p^T p} \tag{4}$$

$$k_2(p) = \kappa e^{-\beta(\log(\gamma p^T p))^2} \tag{5}$$

where k_1 is a Gaussian kernel that generates normal craters where the parameter α controls the depth. In contrast, k_2 generates volcanic craters where κ controls the depth and β and γ define the radii of the outer and the inner ring, respectively. The individual kernels are combined with the weighting factors $w_l \in [0, 1]$ in equation 3. p_l is a simple impulse following a Poisson distribution according to [PGDG16].

Moreover, we want to control the shape of the craters to allow also ellipsoidal shapes. The basic idea is to simply truncate the kernel outside a certain area. By simply setting $k_{1,2} = 0$ in the case that $(p - p_l)^T V^{-1}(p - p_l) > \sigma$ for a diagonal matrix V and a user-definable influence radius σ we can easily achieve this.

These definitions for our macro details have several advantages:

1. By introducing J layers of LCSN we can generate different sizes of craters simultaneously through the scaling of input point $(p - p_l)$ for each layer. Moreover, doubling the scale of the input point also scales the number of craters. This is according to the literature that states the distribution of large size craters and smaller size craters obey an exponential trend [LDB*19].

2. The Poisson distribution of impulses p_l controls the position of craters which leads to a random distribution of the craters (see Figure 2(a)).

3. By introducing the kernel area σ we can achieve shape control while avoiding possible repetitions: normally, the structure generated by the spot kernel relies on a regular grid and within each grid cell, it generates similar pattern. In our case, the density of craters follows the user-definable probability within each grid cell. By defining the kernel area σ and the distribution range of the impulse we can easily control the occurrence of craters to break the repetition on the surface of the asteroid because the impulse position is not limited to one grid cell but includes neighbour areas.

For the generation of boulders we can simply inverse the value of the spot noise and design a different ellipsoidal shapes similar to boulders (see Figure 2(b)). This definition provides intuitive control of the result: the shape of craters (boulders) in each layer can be explicitly authored by setting up the diagonal matrix V, while the distribution of craters in each layer can be achieved by controlling the distribution of impulses and the size of kernel area σ.
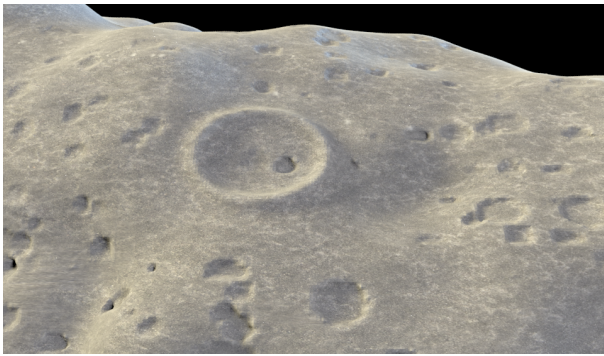
(a)
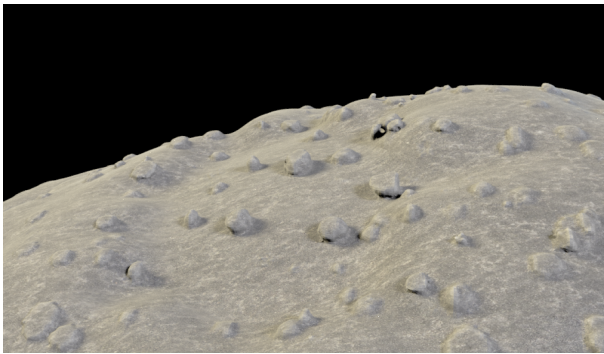
(b)

Figure 2: *(a) The image shows some craters generated by our spot noise model on the implicit surface. With the intuitive noise parameters we can easily change the shape and density of the crater (The big volcanic crater we set $\kappa = -4.9$, $\beta = -10.0$, $\gamma = 0.2$, for the tiny normal craters we set $\alpha = 0.09$). (b) The image shows the corresponding boulders generated by inverting the value of our spot noise model.*

3.2. Micro terrain details

Micro details of terrain can be defined as Gaussian random fields [PP02]. Galerne et al. [GLLD12] proposed a GNBE algorithm using a sparse representation of examplar's power spectrum and a bandwidth-quantized Gabor kernel for the efficient computation. According to Gilt et al. [GSV*14] and Pavie et al. [PGDG16] both LRP and LCSN noise models are able to generate textures from examples. However, LCSN and LRP models focus on synthesizing structured textures and the parameters have to be selected manually. Our goal is a sparse representation of fine terrain details without structures. Actually, GNBE allows a higher level of flexibility in controlling the final results.

The anisotropic bandwidth-quantized Gabor noise [GLLD12] is defined for each point $p \in \mathbb{R}^3$) as

$$gabor\_noise_q(p) = \sum_{b \in B} \frac{1}{\sqrt{\lambda_b}} \sum_i \frac{1}{\sqrt{P_{b,i}}} kernel(p - p_i) \quad (6)$$

with

$$kernel(p - p_i) = K e^{-\pi a^2 |p - p_i|^2} \cos(2\pi(p - p_i) \cdot w + \phi) \quad (7)$$
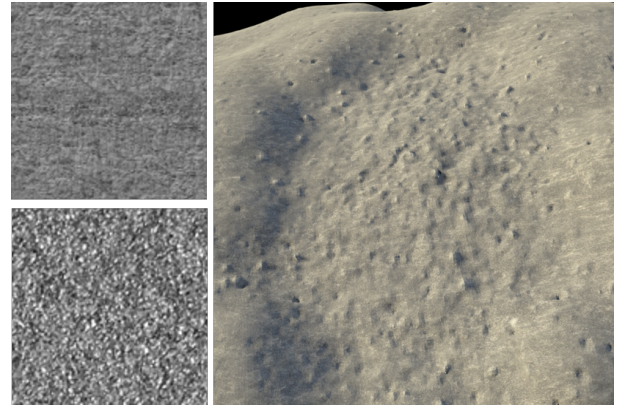

Figure 3: *The left column is the input image, the top image is the texture of a rocky surface and the bottom image shows a sand ground. The right column shows the corresponding terrain details from our example textures.*

where p_i is the impulse following a Poisson distribution and λ and K, w, a and ϕ control the amplitude, frequency, bandwidth, and phase of each Gabor kernel which are randomly chosen from G Gaussian patches, under probability of $P_{b,g} = \lambda_{b,g}/\lambda_b$. We quantize the bandwidth a into a small set of B bandwidths to simplify the parameter estimation By decomposing the example's power spectrum into a sparse sum of Gaussian patches using a non-negative basis pursuit denoising we can compute the parameters of the bandwidth-quantized Gabor noise to fit with the power spectrum of the example Gaussian textures. Here, we evaluate the parameter of example textures (see Figure 3 left) and apply the corresponding parameter into our 3D Gabor noise model to generate similar terrain details (see Figure 3 right).

Like for the LCSN, we also extend the GNBE into three dimensions. The final result is a noise model on an implicit surface. Inspired by Lagae's et.al [LLDD09] surface noise, we simply project the Poisson distribution of impulses onto the tangent space of the implicit surface and compute our noise model within each grid point's tangent space. Due to the essence of volumetric representation our volumetric terrain can easily generate caves or overhangs on the surface of the asteroid which is impossible for traditional 2D grid heightfield methods.

4. Results

We have implemented our system in C++ with the use of OpenGL and GLSL. All examples in this paper were created on a desktop computer equipped with Intel 3GHz Core i7 with 32GB RAM and an NVIDIA GeForce GTX 1080Ti. In order to generate a waterproof mesh we extract the isovalue points from a 3D grid and use a screened Poisson surface reconstruction algorithm [KH13] to generate the final mesh from the extracted point cloud. The output mesh was streamed into Blender to produce photorealistic asteroid surfaces (see Figures 1, 2(a), 2(b), 3, 4, 5, 6).
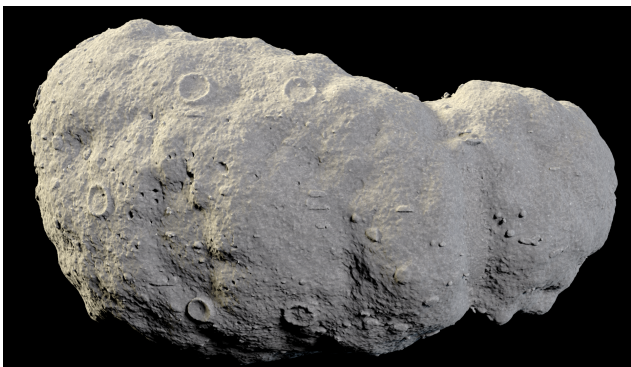
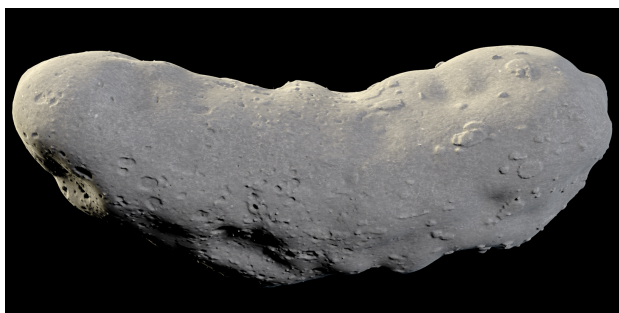**Figure 4:** *Results from our procedural noise model applied to a low resolution Itokawa model.*

Figure 5: *Results from applying our implicite method to represent the asteroid Eros. We show the local control with the right part boulders only and left part a mixture of micro details with different size craters.*

5. Conclusions and Future work

We have presented a novel noise model for generating diverse terrain types on the surface of small celestial bodies. Our noise model combines LCSN with GNBE to synthesis the macro terrain features like craters or boulders and micro details. Moreover, our method provides local control from the metaball positions in the implicit surface, which avoids the globality of traditional procedural texture methods. Also, our approach makes it easy for non-professionals to almost automatically author diverse complex 3D models by changing just a few parameters.

Our results show the quality of the generated terrains and the comprehensibility of the parameters. The performance is dominated by the evaluation of the Gabor noise and locally controlled spot noise patches which is computationally more expensive than computing simple Perlin noise. Even though our implementation is currently not suitable for real-time editing, it can certainly be accelerated further, e.g. improving the computation of Gabor noise [TNVT19]. However, this has to be considered carefully to remain continuity.

In the future, we plan to extend our method to more general use cases, such as terrain covered with icebergs or complex terrestrial terrains including overhangs and caves. Furthermore, our method
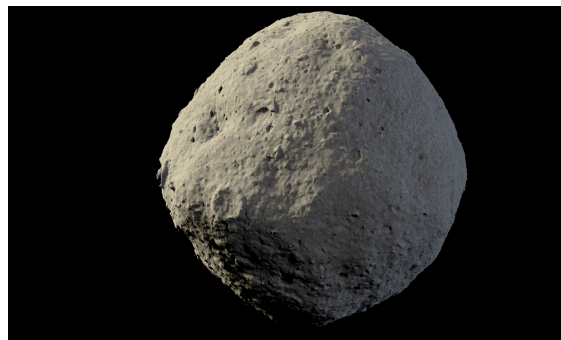

Figure 6: *Our procedural noise model applied to a low resolution model of the asteroid Bennu.*

can be integrated with other terrain synthesis approaches, such as the simulation of physical phenomena, e.g. erosion. Potentially, it could also be applied to more general physical simulations of elastic objects, with volume preservation or even topological changes, which would be essential, for instance, in medical applications.

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