

Real-time Mesh Extraction of Dynamic Volume Data Using GPU

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ABSTRACT

In the paper an algorithm of triangle mesh generation for a full three-dimensional volumetric data is presented. Calculations are performed in real time using graphics processors. The method is very well suited for the visualization of dynamic data, as the calculations use only the current frame data (not including data from previous frames). Due to high performance of the algorithm, it can be practically applied in programs for digital sculpting, simulators and games which require editable geometries.

Keywords

mesh generation, iso-surface, volume data, real-time, GPU computation

1 INTRODUCTION

Nowadays, visualization of volumetric data is very often applied in practice. Both in medicine, e.g. for the MRI, PET, or CT data presentation in medical imaging, nondestructive inspection of materials (industrial CT), digital sculpting software, as well as in computer games. Often the visualization itself is not sufficient and a three-dimensional mesh is required for a physical calculations, such as collision detection, calculation of material properties or stress. Moreover, the advantage of representing models with triangle meshes is that modern GPUs are optimized for efficient rendering of triangles.

Another issue is that volumetric data can change dynamically. When modeling is performed in a program for sculpting a virtual material, a three-dimensional mesh generated in real time is needed in order to display the results. In video games or simulators of earth-moving machineries, we have to deal with the terrain, which cannot be fully represented by height maps. We may require a visualization of structures such as tunnels, caves, overhangs of the land as well as other modifications caused as a result of a player actions, such as explosions, vehicle interactions with the terrain or other gameplay activities.

Currently available methods often do not allow to generate a mesh for a large amount of data in real time.

Sometimes the resulting effect is described as "interactive" which usually means ability to carry out calculations giving a few frames per second. This speed, however, is not sufficient for the smooth operation of applications such as computer games.

In response to these problems, a mesh generation algorithm for a fully three-dimensional volumetric data has been developed. All calculations are performed on GPU in real time by which we understand the actual mean speed of computations above 30 frames per second. Another advantage of the presented algorithm is its independence of the volumetric data representation; therefore, scalar fields, implicit functions, or metaball objects can be used.

The rest of this article is organized as follows. The next section presents previous work on mesh generation methods of volumetric data. The third part briefly describes the possible methods of data representation. It then shows the subsequent steps of the algorithm while in the following passage detailed information on how to implement the algorithm using graphics processors is included. The last section presents a description and summary of results.

2 RELATED WORK

The subject of this paper is to visualize an iso-surface generated for the volumetric data using triangle mesh. Mesh-based methods allow their easy integration with other algorithms or modules, e.g. physics engines, that require mesh as an input. Thanks to this approach our algorithm can be used in real-time applications.

Therefore, discussion of previous works does not include ray-tracing and view-dependent visualization; however, information on the methods of these types can be found e.g. in [OBA05, LK10, GDL⁺02].

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GPU-based methods which allows to interactive or real-time calculations were presented e.g. in [KOKK06, CNLE09, KOR08, TSD07].

One of the basic methods of generating a mesh on the basis of volumetric data is the Marching Cubes algorithm [LC87] developed in the 1980s. It consists in dividing the visualized space into equal cubes and generating a polygon within each cube, which is then subjected to triangulation. The position and shape of the polygon are dependent on the values of an implicit function in eight vertices of each cube. A common issue with this method is that it requires generating a mesh in the entire space of visualized data. In response to this, several hierarchical and adaptive versions of the Marching Cubes algorithm have been developed [OR97, Blo88, WKE99, KKD07] using octal trees to reduce the area for which calculations were carried out and which reduce the number of triangles by generating them in different densities depending on the distance of the camera. Implementations of the Marching Cubes algorithm using GPUs are presented in [JC06, Gei07].

Another, possibly less popular, method is the SurfaceNets method [Gib98] which originally was used to visualize binary medical data. This method is dual to the marching cubes algorithm and, as in the latter one, visualized space is divided into cubes of the same dimensions. In its base version, the method consisted of selecting the nodes belonging to the surface in a way that a certain node has been selected, if among the eight vertices of the cube were those that had a different sign. These nodes were linked with adjacent ones thus creating a net, which was then smoothed by moving the nodes so as to minimize the energy between them while maintaining the restriction that a node could not leave the cube, to which it originally belonged. The final step was a triangulation of the network, which gave the resulting mesh of triangles. The next method which belongs to the group of "dual algorithms" is the one by [Nie04], which generates a mesh very similar to SurfaceNets, but its implementation is more like the Marching Cubes algorithm. One of the important differences between this method and the SurfaceNets is that the mesh generated by the former is a proper two-dimensional manifold.

In addition to the methods outlined above, there are also: the marching tetrahedra method [TPG99], whose operating principle is based on the marching cubes algorithm, the marching triangles method based on the Delaunay triangulation [HSIW96] which generates an irregular mesh, or the method based on marching cubes which allows one to obtain sharp edges, described in the work [JLSW02].

We follow the existing approach of dual marching cubes, however, our algorithm is implemented exclusively on GPU and it efficiently exploits geometry

shaders. Thanks to the use of dual methods, the resulting mesh contains fewer triangles and is regular due to the number of generated triangles within each of the cubes. The latter allows the method to be implemented in a very efficient way using graphics processors. Former GPU-accelerated mesh extraction algorithms (e.g. [KW05], [Goe05], [JC06]) are based on both CPU and GPU computations, using vertex or fragment shaders only. Although meshes generated using our method are not proper two-dimensional manifolds, our approach is extremely efficient and can be used for dynamic data which change on random every frame.

3 VOLUMETRIC DATA

The basic method of describing three-dimensional volumetric data is the implicit function. By setting the values of the contour we obtain surface limiting the desired area. If the values of this function represent the Euclidean distances from a given contour and we save them as an array, then we get a three dimensional signed distance field $D : \mathbb{R}^3 \rightarrow \mathbb{R}$, representing the iso-surface S , defined for point $p \in \mathbb{R}^3$ as:

$$D(p) = \text{sgn}(p) \cdot \min\{|p - q| : q \in S\}, \quad (1)$$

where

$$\text{sgn}(p) = \begin{cases} -1 & \text{if } p \text{ is inside} \\ +1 & \text{if } p \text{ is outside} \end{cases} \quad (2)$$

This representation can be stored in graphics card memory as a three-dimensional texture. Thanks to this representation, smoothing of the resulting mesh using normals computed directly from distance fields and vertex distances from the surface, is very effective.

Also, most medical data is stored in the form of three-dimensional arrays. For such data combined with contour values we can generate a mesh. Another, less common way to represent the volumetric data, is using metaball objects which, with adequate representation, can be converted to distance fields.

4 ALGORITHM OVERVIEW

Due to the GPU architecture and the way they carry out calculations, the developed algorithm is based on dual methods. They allow to obtain a regular mesh consisting of squares, so one doesn't need expensive triangulation of polygons generated inside a cube, as is the case of marching cubes method. The algorithm has been adapted to carry out calculations on GPUs, and highly parallelized, which allows it to achieve very high performance.

Input data block, of size n^3 , where n of a form 2^k , is divided into equal cubes. This is shown in Figure 1.

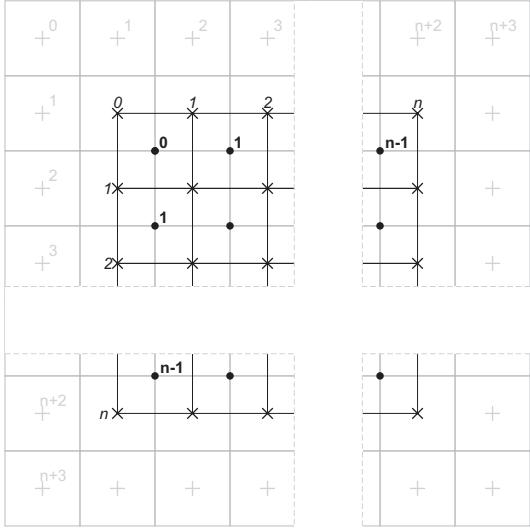


Figure 1: Data organization (2D view)

The image represents a two-dimensional version, but the three-dimensional one is similar.

Calculation points marked with "●" symbol are placed in the centers of cubes and their coordinates are used to calculate the distance from the contour, based on the volumetric data. Distance field values are stored in points marked "+", while points marked "x" represent vertices of quadrangles generated by the algorithm.

The calculations of the algorithm are processed in two steps. At the beginning, for each calculation point $p \in \mathbb{R}^3$, marked with the symbol "●", such that $p \in \{[0, n - 1] \times [0, n - 1] \times [0, n - 1]\}$, there are generated three points $q, r, s \in \mathbb{R}^3$ such that for $p = (x, y, z)$: $q = (x - 1, y, z)$, $r = (x, y - 1, z)$, $s = (x, y, z - 1)$. In each of these points p, q, r, s an implicit function value $d_p = f(p)$ is calculated and three edges defined by pairs of calculation points pq, pr, ps are created. Then, for each edge – if its endpoints have different signs (lie on different sides of the contour) – a quadrangle located on the border of the cubes is generated. Its orientation is determined by the direction of the edge, which is consistent with the direction of the normal to the surface of the quadrangle. A set of squares, generated in this way, approximates the iso-surface for input volumetric data, and is smoothed in the next stage. As a result of conversion of each square to a pair of triangles, a triangle mesh is obtained.

Due to the fact that during the calculation the sign changes, zero is treated differently depending on the direction of the edge, the condition 3, under which quadrilaterals are generated is presented as follows:

$$(f(q) \geq 0 \wedge f(p) < 0) \vee (f(q) < 0 \wedge f(p) \geq 0) \quad (3)$$

The first step in the algorithm, described above, is ideally suited for parallelization, because the calculations

for computing the individual points can be carried out independently. Despite the fact that the distance fields are calculated for each point twice, it is possible to obtain a high-performance computing algorithm, because it is not a costly operation.

The second stage of the algorithm is a smoothing of generated mesh by moving its vertices in the direction of the surface represented by the distance fields values. For this purpose, at each vertex of the distance field, a normal vector n is calculated on the basis of the gradient and the distance d to the surface. Then, the vertex is moved in the direction of the normal, by the value calculated according to formula 4.

$$p' = p + dn \quad (4)$$

In the case that the resulting mesh is used only for displaying a surface, this step can be implemented directly during rendering. Otherwise, it is possible to smooth the mesh only and use it for subsequent calculations, such as collision detection.

The advantage of the developed algorithm over marching cubes method consists partly in that for creating a quad for the cube we generate exactly four indices and there is no need for triangulation of polygons generated. This allows the calculations to be successfully performed on the GPU.

5 IMPLEMENTATION DETAILS

The algorithm was implemented using the OpenGL graphics library; however, DirectX library can be used as well.

Input volumetric data, for which a mesh is generated, is divided into equal blocks, for which fragments of the mesh are generated independently. This approach was chosen because of the GPU hardware limitations on the maximum size of supported textures, as well as for optimization purposes. To be specific: not all parts of dynamic data need to be modified at the same time, and hence there is no need for mesh regeneration in these blocks. Generated meshes merge together in continuous blocks along borders.

The algorithm is carried out equally for each data block. All calculations are done on the GPU, so the data are not transferred between main memory and graphics card memory. Calculations are carried out in two phases, the algorithm flowchart is shown in Figure 2.

In both passes of the rendering shaders refer to the volumetric data.

5.1 Volume Representation

Three-dimensional floating-point texture is used for distance field representation in each block of data.

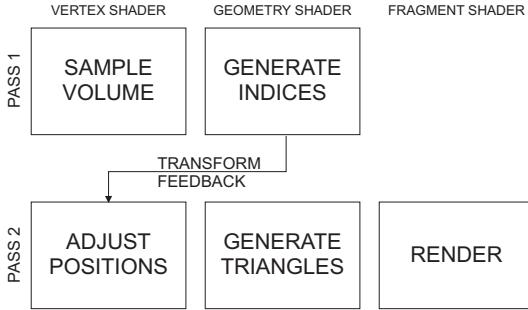


Figure 2: Algorithm flowchart

Texture size is $(n+3)^3$, 2 bytes per texel. Although 4-byte floating point numbers can be applied for the precision improvement, no need for that has been found during testing. To avoid communication between neighboring blocks, block's data size is enlarged and overlaps adjacent blocks; for each common quadrangle between two adjacent blocks of size $(n+3)^3$ each, $2n^2$ of voxels are duplicated. This allows parts of the mesh in each block to be generated independently of the others.

In the texture, we used a single GL_RED channel, where the data is stored in GL_FLOAT16 format. In order to allow reading distance field values, each point of the texture is sampled using linear filtering. This is done automatically, and the values are calculated on the basis of neighboring texels. Mipmaps for the textures are not generated.

5.2 Mesh Generation (Pass 1)

In the first pass calculations are performed using vertex shader and geometry shader. Then, using a transform feedback, generated indices are stored in the output buffer. Input and output data are presented in Table 1.

IN
Vertex buffer containing calculation points $p \in \{[0, n-1] \times [0, n-1]\}$ type: GL_ARRAY_BUFFER size: $(n-1)^2$ sharing: one per all blocks
Texture with volumetric data type: GL_TEXTURE_3D size: $(n+3)^3$ sharing: one per single block
OUT
Buffer with indices of generated quads type: GL_ELEMENT_ARRAY_BUFFER sharing: one per single block

Table 1: Input and output data of the first pass

The subsequent steps of the algorithm are as follows:

1. Data from the vertex buffer containing the calculation points is rendered $n-1$ times, using the instance rendering.

2. For a calculation point p three points q, r, s are created in the vertex shader.

3. For each of the points p, q, r, s a volumetric texture is sampled in order to retrieve implicit function value. Texture coordinates t are calculated according to formula 5.

$$t = \frac{p+2}{n+3} \quad (5)$$

4. Subsequently three edges pq, pr, ps are created and according to formula 3 it is checked whether the values of implicit function at the endpoints have different signs.

5. For each edge, if the sign changes, there is a flag set, which specifies whether the quadrilateral is generated or not, and what is its orientation (zero means that the quadrilateral is not generated). Generated flags along with the coordinates of the point p are forwarded to the geometry shader.

6. In the geometry shader, for each non-zero flag there a vertex containing four indices of generated quadrangles is established. Indices are calculated on the basis of the flag f and coordinates p . For example, quadrangle, which normal is consistent with the direction of the edge pq , is defined by (i_1, i_2, i_4, i_3) , where

$$\begin{aligned} i_1 &= p_x n^2 + p_y n + p_{z+1} \\ i_2 &= p_x n^2 + p_{y+1} n + p_{z+1} \\ i_3 &= p_x n^2 + p_{y+1} n + p_z \\ i_4 &= p_x n^2 + p_y n + p_z \end{aligned}$$

7. Using the feedback transformation these indices are stored directly in the index buffer, used in the next pass. Number of saved indices is queried using an OpenGL query mechanism.

5.3 Rendering (pass 2)

The second pass is responsible for smoothing of the generated mesh and its rendering. All programmable shader units, i.e. vertex, fragment and geometry shaders are used. The input data is presented in Table 2.

Subsequent steps of the second pass of the algorithm are as follows:

1. The data from the vertex buffer is rendered using the indices as primitives of the GL_LINES_ADJACENCY type. This type was chosen because it is the only type that can render

IN
Vertex buffer which contains all potential vertices, such as: $u \in \{[0, n] \times [0, n] \times [0, n]\}$. <i>type</i> : GL_ARRAY_BUFFER <i>size</i> : n^3 <i>sharing</i> : one per all blocks
Buffer with indices for generated quadrangles <i>type</i> : GL_ELEMENT_ARRAY_BUFFER <i>sharing</i> : one per single block
Texture with volumetric data <i>type</i> : GL_TEXTURE_3D <i>size</i> : $(n + 3)^3$ <i>sharing</i> : one per single block

Table 2: Input data for the second pass of the algorithm

primitives indexed by four indices (in OpenGL version 3.0 or higher it is not possible to render quadrangles).

2. Then in the vertex shader for each vertex u , a normal vector n is calculated, on the basis of the gradient map. Normal value is obtained by sampling the volumetric data texture in the neighboring six texels in x, y, z directions.
3. On the basis of the direction of the normal and the density function value, the point u is moved in the direction of the contour, according to formula 4. Due to the fact that the value of the density function is calculated as the average of neighboring texels at the point u , for small values of n it is required to perform a smoothing of the mesh in an iterative manner.
4. Vertices calculated in this way are sent to the geometry shader, in which there is a change of type done, from "lines adjacency" into "triangle strip".
5. The last step is to display a completed mesh, during which the associated shading calculations are performed in the fragment shader. In case when mesh rendering is not required, but the mesh is needed for further calculations, smoothed values of the vertices can be stored in the output buffer using a transform feedback.

6 RESULTS

All calculations were performed on an AMD Phenom II X6 1090T 3.2GHz computer with an nVidia GeForce GTX 460 graphics card. Figure 3 presents datasets used in tests; Armadillo and Asian Dragon from *The Stanford 3D Scanning Repository*, Engine and Skull from <http://www.volvis.org/>. In addition, three-dimensional animated Perlin noise has been used as a dynamic, time-dependent data. All tests were run for different n on one block of data.

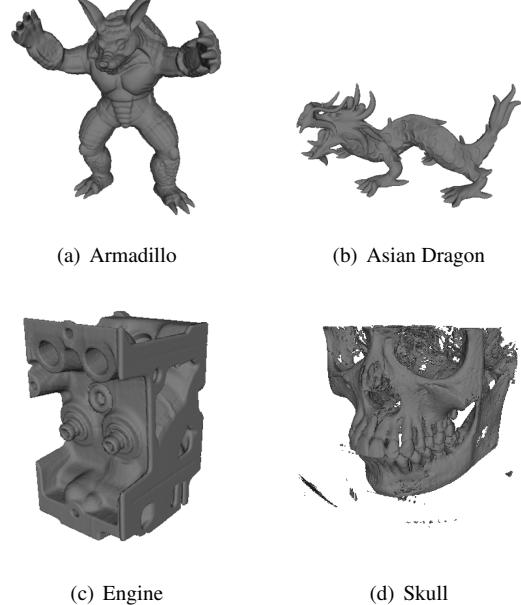


Figure 3: Datasets used for tests

Table 3 lists times for mesh generation and rendering for different block sizes and different data sets. All meshes were regenerated from volumetric data each frame; moreover, calculations for time-dependent Perlin noise data were also performed before mesh generation every frame. Generated meshes for the Armadillo dataset for different block sizes are presented on figure 4, results for noise dataset are presented on figure 6.

dataset	n	triangle count	fps
Armadillo	64	14180	1100
Armadillo	128	91958	208
Armadillo	256	494880	28
Asian Dragon	64	5864	1180
Asian Dragon	128	41578	234
Asian Dragon	256	229840	30
Engine	256	592884	29
Skull	256	1699526	23.6
Perlin Noise	128	180k-246k	60

Table 3: Results for different block sizes and data sets

Table 4 presents results for our method compared to [Goe05, JC06]. The Engine and Skull datasets were used, no preprocessing were performed for these data. As it can be seen our algorithm performs much faster, however, if all methods would be run on the same hardware configuration, the difference could be less significant. Both methods of [Goe05] and [JC06] were tested on nVidia GeForce 6800GT graphics card.

The Marching Cubes algorithm described in [Gei07] seems to execute faster than [Goe05, JC06] methods but no measurable results were published. Authors of [Gei07] claims that their algorithm executes in interac-

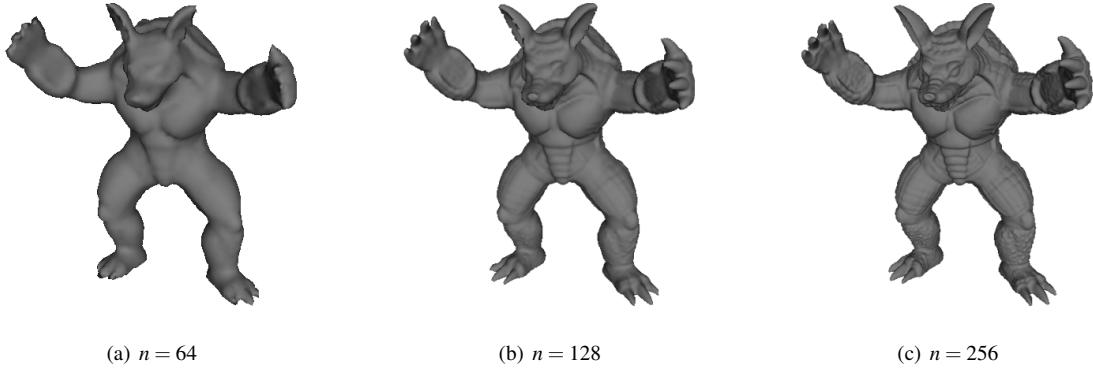


Figure 4: Generated mesh for the Armadillo dataset

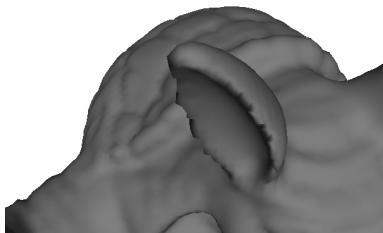
tive frames but mesh generation are not performed each frame.

dataset	size	method	fps
engine	256x256x110	[Goe05]	3.6
engine	256x256x128	[JC06]	2.8
engine	256x256x256	our method	29
skull	256x256x225	[Goe05]	2.4
skull	256x256x256	[JC06]	1.5
skull	256x256x256	our method	23.6

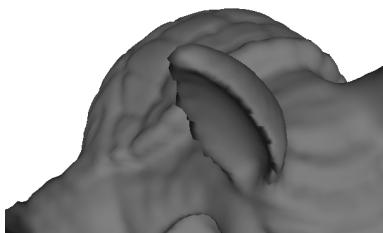
Table 4: Results compared to previous GPU-based methods

7 MESH IMPROVEMENTS

The presented method works well for smooth surfaces, such as the ones presented in figure 6. In case of surfaces with sharp edges we see artifacts as it is shown in figure 5(a).



(a) Artifacts on sharp edges



(b) Smoothed mesh

Figure 5: Mesh improvements due to smoothing

In order to improve visual quality of the generated surface, in the second pass of the algorithm a smoothing

process based on normals is performed about 10 times. Next, during transforming quadrangles into strips of triangles, the quadrangles are divided along the shorter diagonal. The last step of smoothing the mesh is computation of normals for every pixel in fragment shader, on the basis of volumetric data. Normals are calculated in the same way as for the mesh vertices. The smoothed mesh is presented in Figure 5(b).

8 CONCLUSION AND FUTURE WORK

In this paper we present a real-time algorithm for generating a three-dimensional mesh fully based on volumetric data. This method has been optimized for graphics processors and provides a significant advantage over the already existing solutions for conventional processors. The presented algorithm is also very well suited for the visualization of dynamic data, because the calculations carried out do not need to know the state of the algorithm from previous time steps.

With the resulting performance, practical application of the algorithm in digital sculpting software, earth-moving machineries simulators and computer games is fully possible. The tests show a significant advantage of GPUs. The volumetric data representation that has been used allows also for efficient data modification using GPUs.

As part of further work on the algorithm it would be reasonable to add support for levels of detail (LOD), so as to enable the process to connect continuously adjacent blocks containing cubes of different sizes and densities.

The second issue is to optimize the algorithm by an additional parallelization and simultaneous calculation carried out for 4 blocks. It would be possible in the case of using all four available texture channels. As a result, it would be possible to generate meshes for the four blocks at the same time.

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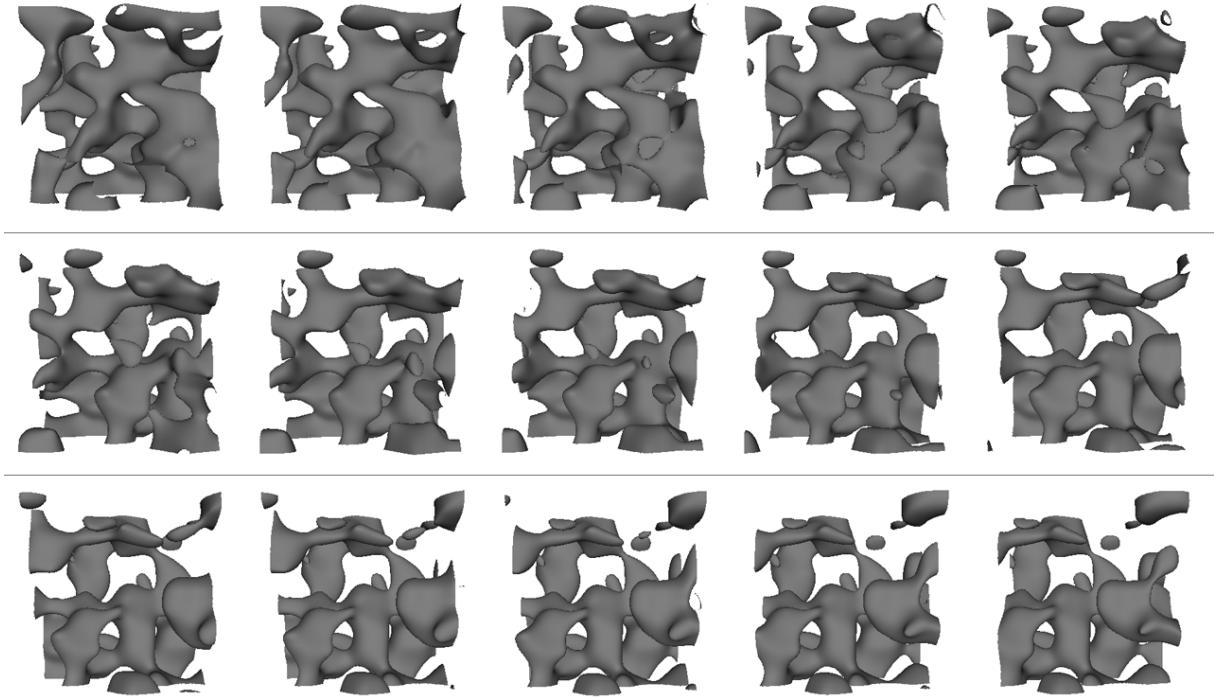


Figure 6: Generated meshes for Perlin noise dataset for 15 frames

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