GigaVoxels, Real-time Voxel-based Library to Render Large and Detailed Objects
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What is all about?

R&D project about real-time exploration of
- large and detailed objects/scenes
- eventually generated on the fly
- visually realistic

Target audience
- Video games
- Special effects
- Special case: scientific visualization

voxel based medical dataset generated from CT scan (2048x2048x2048, 32GB on disc)
Goal

Present our implementation of the « GigaVoxels » technology

- Reminder: what is GigaVoxels? – Key Concepts / Features
- Show fonctionnalities through examples of the SDK
- A survey: explain how to program
Exploratory Research phase

- PhD Thesis: « GigaVoxels: A Voxel-Based Rendering Pipeline For Efficient Exploration Of Large And Detailed Scenes »
- Team: INRIA/CNRS/LJK (Cyril Crassin, Fabrice Neyret)
- Based on an OpenGL / GLSL + CUDA prototype

Engineering phase

- Started in 2011: clean, maintain, add fonctionnalities, ...
- SDK (tutorials), doc, tools, ...

Partnership

- RSA Cosmos: planetariums [funded by French ANR, 4 years research project]
Website

- image gallery
- videos
- publications
- documentation
- source code (not yet)
- contact

http://gigavoxels.inrialpes.fr/
Key Ideas

[x] Rendering only dependent on what is visible
   - ray-tracing approach

[x] Load only needed data, at the needed resolution
   - occlusion + LOD (level of details)
   - ray-guided streaming

[x] Reuse loaded data as much as possible
   - cache mechanism on GPU

[x] Minimize computation, minimize memory transfers
Key Features

- **Tree Data Management** (space partitioning) to store and organize data (octree or generalized N3-tree, + SDK example kd-tree)
- **Cache System on GPU**: LRU mechanism (least recently used) (to get temporal coherency)
- **Data Production Management**: on host, GPU, or hybrid mode
  Goal: produced data are kept in cache on GPU
- **Visit algorithm**: traverse your data (loaded in cache) as could be done for rendering
- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)
Data Structure

Generalized N₃-tree (octree)
- Space partitioning
- Empty space compaction

Bricks of voxels
- Linked by octree nodes
- Store opacity, color, normal,…

“Node pointer based” data structure

<table>
<thead>
<tr>
<th>Node Texel</th>
<th>Nodes Tile pointer</th>
<th>Constant color</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Address</td>
<td>R G B A</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>8 8 8 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unused or Brick pointer</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>X Y Z</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

N₃-Tree

Mip-Map Pyramid with stored bricks
GigaVoxels Pipeline

- **GPU**
  - Sparse Voxel Octree
  - Voxel Ray-Tracer
  - Output image
  - Data usage + requests
  - Structure updates
  - Voxel data fetch

- **CPU**
  - Central Memory Store
  - Mass storage

- **Manager**
  - GPU Cache Manager
GigaVoxels Pipeline + data structure

- unified data structure (geometry + texture)
- load only needed data at needed resolution
- smooth transitions and continuously reveals details
- Handle semi-transparent objects
- Alias free filtered images (cone tracing)
PART 2 - Fonctionnalities through SDK examples
Data loading

**Data streaming**

Load data « on demand ». Two modes :
- level by level (from coarse to fine) [ speed trade-off ]
- directly max level of resolution [ quality before ]

**File format**

By level of resolution and by data types
- 1 - nodes (spatial structure)
- 2 - bricks of voxels
no header, no meta-file...
Import your own data

**Custom file importer**

RAW data [scientific visualization]

- apply transfer function
- threshold data
- clipping plane [region of interest]
Procedural data generation

Mandelbulb

Goal: generate environments

Fractal object: 3D extension of Mandelbrot set

\[
(x, y, z)^n = r^n (\cos(n\theta) \cos(n\phi), \sin(n\theta) \cos(n\phi), \sin(n\phi))
\]

où \( \begin{cases} 
 r &= \sqrt{x^2 + y^2 + z^2} \\
 \theta &= \arctan(y/x) \\
 \phi &= \arctan(z/\sqrt{x^2 + y^2}) = \arcsin(z/r)
\end{cases} \)

pour la nième puissance du nombre hypercomplexe 3D. Les points sont calculés par itération de \( z \mapsto z^n + c \) où \( z \) et \( c \) sont des nombres hypercomplexes dans un espace de dimension 3 et \( z \mapsto z^n \) l’application définie ci-dessus. Ici \( n = 8 \).
Procedural data generation

Mandelbulb
Noise - Hypertextures

Goals
Add details on 3D models
- smooth transitions and continuously reveals details
- alias free filtered images
- handle parallax effect

Theory
- Ken Perlin
- book: « Texturing and Modeling, a procedural approach », chapter 12
Noise

Input

3D model : Signed Distance Field
- Noise : applied on distance and normal
- Transfer Function : convert distance to RGBA color
Idea: (use cache)

Mimic the LOD mechanism that continuously add details:

- Re-use noise computation at previous resolution level
- Noise: sum of octaves (frequencies)
- Compute only one octave by level of resolution
- Store them in GPU cache
- Reproduce the sum:
  
  $F(\text{level } N) = \text{currentNoise}(\text{level } N) + \text{previousNoise}(\text{level } N-1)$

Finally: replace “noise computation” by “data fetch in cache”
Hypertexture (shape + solid texturing)

- $F(x) = 0$: outside the object
- $F(x) = 1$: strictly inside the object
- $0 < F(x) < 1$: inside a fuzzy region

Idea: add details on armor soldier

- Distance function: sphere
- Thickness: fuzzy region (Perlin noise)
- Current work: optimizations
  - Stop adding noise components if density is outside
Hypertextures
Depth of Field

Goal

Add more realism to images
- mimic camera lens (focus plane)
- double lens cone
Voxel data synthesis

**Goal**: Simulate environments

**Instanciation and recursion**
- node pointers based system

---

**Instanciation**

**Recursivity**
Voxel data synthesis

Menger/Serpinski Sponge
Mix triangles and voxels

- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels
**Goal** (not yet, in study/progress)

Have several GigaVoxels entities (forest)
- Need proxy geometry
- Render projected 2D BBox
- Use GLSL fragment shader
- (rays start + direction)
**Goal**

Environment to study, test, profile, debug...
- Kind of “generic” API: browsers, editors, etc...
- Tools: transfer function, performance monitor, etc...
- 3D models importer (+ GLSL shaders editor)
- Futur hope:
  - CUDA functions editor
  - “recompile on the fly”
Goal

Plugin « GigaVoxels Pipeline » : dynamic library (.dll, .so)

=> kind of « effect »

- Idea : plug this “node” in a scene graph à la OpenSceneGraph (see the “ppu” project) or Ogre3D

- Not yet finished : it has been “polluted” with Qt to have USER custom editors.
Pre-process step
Future work:
- optimize code
- smooth resulting data
- idea: voxelize data
  “on the fly” in the producers
Use events to record time between kernel functions

Special case: record "device" functions (1 thread per pixel)
```c
#include <time.h>

__device__ unsigned uint64 getClock()
{
    unsigned result;
    // Using inline PTX assembly in CUDA.
    // Target ISA Notes : %clock64 requires sm_20 or higher.
    //
    // The constraint on output is "=l" :
    // - '=' modifier specified that the register is written to
    // - 'l' modifier refers to the register type "u64 reg"
    asm volatile("mov.u64 %0,%clock64;" : "=l"(result) : :);
    return result;
}
```
French ANR Research Project
RSA Cosmos: planetariums [2010-2014]

- “Real-Time and Interactive Galaxy for Edutainment”
- I. Visualize static galaxies
- II. Data amplification (procedural generation)
- III. Animate galaxies

Optimisations
- use OpenGL billboards to stop rays (VBO)
- multi-GPUs?
- time budget?, priority on bricks?
PART 3 - The library

- [ 1 ] - Core library
- [ 2 ] - User custom API
The library

Goal

- Capitalize on the knowledge of the team
- Continue research on the subject
- Hide the complexity of the underlying « core » library (cache mechanism, data structure management, etc...)
- Give USER access to customize the « data production » and the « shader »
The library

Technologies
- C++ (template)
- GPU Computing : CUDA + libraries (cudpp / thrust)
- CMake
- IHM : Qt
- Viewer : QGLViewer
- 3D : OpenGL (GLSL)
- Others : Loki, Assimp, CImg, ImageMagick
- OS : Windows (7), Linux (Ubuntu) + 32/64 bits
- Requirements : Cuda 4.x and Compute Capability SM at least 2.0
[ 1 ] - **Common API**: « hidden » generic mechanisms

- **Tree Data Management** (space partitioning) to store and organize data (octree or generalized N3-tree, + SDK example kd-tree)

- **Cache System on GPU**: LRU mechanism (least recently used) (to get temporal coherency)

- **Data Production Management**: on host, GPU, or hybrid mode
  Goal: produced data are kept in cache on GPU

- **Visit algorithm**: traverse your data (loaded in cache) as could be done for rendering

- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)
[2] – USER access

USER Customizable API

- **Producer** (load or produce our own data)
  - used during Data Production Management

- **Shader** (write your custom shader)
  - used during Visit algorithm and Rendering
Data Production Management:

- Nodes subdivision (data refinement)
- Load or compute bricks of voxels (fill data)

USER has to write:

- a HOST producer
- and its associated GPU producer
Data Production Management

**Sequence Diagram of a frame:**

1. **Visit Data**
   - **KERNEL (2D) Ray-Casting**
   - **1 thread/pixel**
   - **Tree Traversal**
   - **Ray Marching**
   - **CUSTOM shader**
   - **Emit Requests (if needed)**

2. **Handle Requests**
   - **Subdivide Nodes**
     - **HOST** → **GPU**
     - **CUSTOM producer**
   - **Fill Voxels Data**
     - **HOST** → **GPU**

A: **1**
B: **2**
Sequence

Frame 1
Produce Nodes
Produce Bricks

Frame 2
Produce Nodes
Produce Bricks

... 

Frame N
Produce Nodes
Produce Bricks
Nodes subdivision:

- KERNEL: 1 bloc/node and 1 thread/child_node
- Each node has to say what’s inside each of its child
- INPUT: localization info of current node (LOD depth and spatial index pos)
- INPUT: address in “node cache” where to write new child nodes
- Test if it is in a sphere (analytically)
- Write nodes in cache

Ex: sphere on GPU
Nodes subdivision:

WORLD: sphere

Parent

Children
- what’s inside?

1st step
FLAG Children
- EMPTY
- DATA inside
- MAX RESOLUTION reached

Write result in cache
- Next frame, renderer will ask for the node data production (brick of voxels)

2nd step
Retrieve 3D world position with help of INPUT localization info (depth, index position)
Bricks of voxels production:
(same principe as for nodes)

- KERNEL: 1 bloc/brick and thread is as you want
- USER is in 1 brick and has to populate its voxels
- INPUT: localization info of current node (LOD depth and spatial index pos)
- INPUT: address in “data cache” where to write new voxels
- Write voxels in cache

Ex: sphere on GPU
Ex: sphere on GPU

Reminder: SHADER management

1. Visit Data
   - KERNEL (2D) Ray-Casting
     - 1 thread/pixel

2. Handle Requests
   - Emit Requests (if needed)
     - Ray Marching
     - Tree Traversal

- Subdivide Nodes: HOST → GPU
- CUSTOM producer
- Fill Voxels Data: HOST → GPU
SHADER:

- INPUT: “data sampler” and current position
- Sample data, retrieve USER defined channel (color, normal, etc...) and accumulate color along the current ray

// Retrieve first channel element : color
__device__ void ShaderKernel::run( const SamplerType& brickSampler, ... )
{
    float4 color = brickSampler.getValue<0>(coneAperture);  // channel 0 is color

    If ( color.w > 0.0f ) { _accumulatedColor = _accumulatedColor + ( 1.0f - _accumulatedColor.w ) * color; }
SHADER:
- CUSTOM api provide “other entry points”:
- getConicAperture() [modify cone aperture]
- getStopCriterion() [ex: accumulatedColor.w >= 0.98f]
- getDescentCriterion() [used during “visit” traversal]
- ...

GigaVoxels Sequence Diagram
Tips and tricks:

- Template meta-programmation: curiously recursive template pattern (to avoid polymorphism on GPU)

This technique achieves a similar effect to the use of virtual functions, without the costs (and some flexibility) of dynamic polymorphism.

- Data cache: 3D texture to read, and bind with surfaces to write data

- Loki: use to access different textures types

- Cudpp/thrust: cache mechanism on GPU (stream compaction to get “used” and “non-used” elements at current frame)

- Write Z-buffer: slow => idea => use color and do conversion
OpenGL interoperability

Mix triangles and voxels:
- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels
- Opaque objects rendered first (depth buffer) to skip occluded parts
- GigaVoxels registers « textures, renderBuffer, PBO, ... » with optimized flags
(see GTC 2013 : S3070 – « Part 1 – Configuring, Programming and Debugging Applications for Multi-GPUs » from Wil Braithwaite [NVidia]
cudaGraphicsRegisterFlagsReadOnly, cudaGraphicsRegisterFlagsWriteDiscard, ... )
OpenGL interoperability

Mix triangles and voxels

Simple mode: [ no input ] + [ only write color ]

```c
// [ 1 ] - Init texture (with window size)
glGenTextures( 1, &colorTex );
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
gTexImage2D( GL_TEXTURE_RECTANGLE_EXT, 0, GL_RGBA8, width, height, 0, GL_RGBA, GL_UNSIGNED_BYTE, NULL );

// [ 2 ] - Register texture in WRITE ONLY slot in GigaVoxels
renderer->connect( Gv::eColorWriteSlot, colorTex, GL_TEXTURE_RECTANGLE_EXT );

// Launch GigaVoxels rendering engine
renderer->render( /*OpenGL matrices*/ );

// Draw a full screen textured quad
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
gBegin( GL_QUADS );
...```

```c
enum GraphicsResourceSlot
{
    eColorReadSlot,
    eColorWriteSlot,
    eColorReadWriteSlot,
    eDepthReadSlot,
    eDepthWriteSlot,
    eDepthReadWriteSlot,
    eNbGraphicsResourceSlots
};
```
Current work

[ 1 ] - Proxy geometry
“rasterized (approximate) geometry” containing non-empty areas of volume, providing starting and exit point for each ray, speeding-up the skipping of empty spaces
- Help skip empty regions
- Can add volumetric details on a triangle mesh
- Would like to have demo with forest
Current work: based on a galaxy visualization research project

Number of stars represented by points (VBO) can be very huge:

[1] Sphere Ray-Tracing (change representation)
- When bricks are near empty, generate spheres coordinates in « producer »
- Replace brick-marching by Ray-Tracing at rendering phase (fetch positions)

[2] VBO generation
- add details by generating stars (OpenGL vbo points) in a GigaVoxels « producer »
- dump result in VBO dynamically (only visible nodes)
- => kind of view frustum culling
... the futur...

Ideas

- Working on performance (Visual Profiler, NSight)
  - Handle time budget for a frame, priority on bricks
- Use CUDA 5: linker (recompile USER functions on the fly?)
- Store points inside voxel (VBO generation according to visibility)
  - Geometry instancing (forest)
  - Voxel animation (with shellmaps)

...
Library / SDK content

- Core library documented
- SDK tutorials fully documented
- Developer guide: soon
  - kind of “behind the scene”): technical implementations detailed
Thanks

- Fabrice Neyret (CNRS, INRIA, LJK), M. Armand, E. Heitz, E. Eisemann, ...
- Cyril Crassin (NVidia)
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- RSA Cosmos: for testing the library
- French Research ANR:

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Questions

Thanks for your attention

http://gigavoxels.inrialpes.fr/