Multi-Resolution Techniques for Exploring Extremely Large and Complex Surfaces

Enrico Gobbetti and Fabio Marton

Eurographics 2006 Tutorial

CRS4 Visual Computing
Goal and Motivation

Accurate interactive inspection of very large models (unlimited size!) on PC platforms...

All three models at the same time...
(Source: The Digital Michelangelo Project, Lawrence Livermore National Labs, and The Boeing Corporation)

Input geometry: 1.2G triangles
Multiresolution data size: 41.6 GB
Maximum resident set size: 172 MB

Xeon 2.4GHz / 1GB RAM / 70GB SCSI 320 Disk / NVIDIA 6800GTS
Size matters! Or does it? (1/10)
A real-time data filtering problem!

- Models of unbounded complexity on limited computers
  - We assume less data on screen \( (N) \) than in model \( (K \rightarrow \infty) \)
  - Need for output-sensitive techniques \( (O(N), \text{not } O(K)) \)

View parameters

Storage

Limited bandwidth
(network/disk/RAM/CPU/PCIe/GPU/...)

O(K=unbounded) bytes
(triangles, points, ...)

Screen

10-100 Hz
O(N=1M-100M) pixels
Size matters! Or does it? (2/10)

Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = O(N) (independent of K)
Size matters! Or does it? (3/10)
Out-of-core output-sensitive techniques
Goal: Time/Memory Complexity = O(N) (independent of K)
Size matters! Or does it? (4/10)

Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = O(N) (independent of K)

Multiresolution + ...
Size matters! Or does it? (5/10)

Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = O(N) (independent of K)

Multiresolution + View dependent LOD selection + ...
Size matters! Or does it? (6/10)
Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = O(N) (independent of K)

Multiresolution + View dependent LOD selection + View culling + …
Size matters! Or does it? (7/10)
Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = O(N) (independent of K)

Multiresolution + View dependent LOD selection + View culling + Occlusion culling + ...
Size matters! Or does it? (8/10)

Out-of-core output-sensitive techniques

Goal: Time/Memory Complexity = \(O(N)\) (independent of \(K\))

Multiresolution + View dependent LOD selection + View culling + Occlusion culling + External memory management/Compression
Size matters! Or does it? (9/10)
Out-of-core output-sensitive techniques

• At **preprocessing**
  time: build MR hierarchy
  - Data prefiltering!
  - Visibility + simplification
  - Not output sensitive

[Diagram of multi-resolution hierarchy with labels COARSE and FINE]

CRS4 Visual Computing Group

Multi-Resolution Techniques for Exploring Extremely Large and Complex Surfaces
Enrico Gobbetti and Fabio Marton, Eurographics 2006 Tutorial
Size matters! Or does it? (10/10)

**Out-of-core output-sensitive techniques**

- At **preprocessing** time: build MR hierarchy
  - Data prefiltering!
  - Visibility + simplification
  - Not output sensitive

- At **run-time**: selective view-dependent refinement from out-of-core data
  - Must be output sensitive
  - Access to prefiltered data under real-time constraints
  - Visibility + LOD
Our contributions
GPU-friendly output-sensitive techniques

- Underlying ideas
  - **Chunk-based multiresolution structures**
    - Combine space partitioning + level of detail
    - Same structure used for visibility and detail culling
  - **Seamless combination of chunks**
    - Dependencies ensure consistency at the level of chunks
  - **Complex rendering primitives**
    - GPU programming features
    - Curvilinear patches, view-dependent voxels, ...
  - **Chunk-based external memory management**
    - Compression/decompression, block transfers, caching
Our contributions

GPU-friendly output-sensitive techniques

**BDAM - Local Terrain Models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*EUROGRAPHICS 2003*

**P-BDAM - Planetary terrain models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*IEEE Visualization 2003*

**Adaptive Tetrapuzzles – Dense meshes**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*SIGGRAPH 2004*

**Layered Point Clouds – Dense clouds**
Gobbetti/Marton (CRS4)
*SPBG 2004 / Computers & Graphics 2004*

**Far Voxels – General**
Gobbetti/Marton (CRS4)
*SIGGRAPH 2005*
Our contributions

GPU-friendly output-sensitive techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Authors</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDAM - Local Terrain Models</td>
<td>Gobbetti/Marton (CRS4),</td>
<td>EUROGRAPHICS 2003</td>
</tr>
<tr>
<td></td>
<td>Cignoni/Ganovelli/Ponchio/Scopigno (CNR)</td>
<td></td>
</tr>
<tr>
<td>P-BDAM - Planetary terrain models</td>
<td>Gobbetti/Marton (CRS4),</td>
<td>IEEE Visualization 2003</td>
</tr>
<tr>
<td></td>
<td>Cignoni/Ganovelli/Ponchio/Scopigno (CNR)</td>
<td></td>
</tr>
<tr>
<td>Adaptive Tetrapuzzles – Dense meshes</td>
<td>Gobbetti/Marton (CRS4),</td>
<td>SIGGRAPH 2004</td>
</tr>
<tr>
<td></td>
<td>Cignoni/Ganovelli/Ponchio/Scopigno (CNR)</td>
<td></td>
</tr>
<tr>
<td>Layered Point Clouds – Dense clouds</td>
<td>Gobbetti/Marton (CRS4)</td>
<td>SPBG 2004 / Computers &amp; Graphics 2004</td>
</tr>
<tr>
<td>Far Voxels – General</td>
<td>Gobbetti/Marton (CRS4)</td>
<td>SIGGRAPH 2005</td>
</tr>
</tbody>
</table>
Our contributions

GPU-friendly output-sensitive techniques

**BDAM - Local Terrain Models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*EUROGRAPHICS 2003*

**P-BDAM - Planetary terrain models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*IEEE Visualization 2003*

**Adaptive Tetrapuzzles – Dense meshes**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
*SIGGRAPH 2004*

**Layered Point Clouds – Dense clouds**
Gobbetti/Marton (CRS4)
*SPBG 2004 / Computers & Graphics 2004*

**Far Voxels – General**
Gobbetti/Marton (CRS4)
*SIGGRAPH 2005*
Our contributions

GPU-friendly output-sensitive techniques

- **BDAM - Local Terrain Models**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *EUROGRAPHICS 2003*

- **P-BDAM - Planetary terrain models**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *IEEE Visualization 2003*

- **Adaptive Tetrapuzzles – Dense meshes**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *SIGGRAPH 2004*

- **Layered Point Clouds – Dense clouds**
  Gobbetti/Marton (CRS4)
  *SPBG 2004 / Computers & Graphics 2004*

- **Far Voxels – General**
  Gobbetti/Marton (CRS4)
  *SIGGRAPH 2005*
Chunked Multi Triangulations

The Multi Triangulation Framework

- Theoretical basis
  - MT multiresolution framework (Puppo 1996)

- Our contribution
  - GPU friendly implementation based on surface chunks with boundary constraints
  - Optimized implicit specializations (TetraPuzzles/V-Partitions)
  - Parallel out-of-core pre-processing and out-of-core run-time

Cignoni, Ganovelli, Gobbetti, Marton, Ponchio, and Scopigno.
**Batched Multi Triangulation.**
**Chunked Multi Triangulations**

**The Multi Triangulation Framework**

- Consider a sequence of local modifications over a given description $D$
  - Each modification replaces a portion of the domain with a different conforming portion (simplified)
  - $f_i$ floor
  - $g_i$ the new fragment

\[
D' = D \setminus f \cup g
\]

\[
D_{i+1} = D_i \oplus g_{i+1}
\]
Chunked Multi Triangulations
The Multi Triangulation Framework

- Dependencies between modifications can be arranged in a DAG
Chunked Multi Triangulations
The Multi Triangulation Framework

- Dependencies between modifications can be arranged in a DAG
  - Adding a sink to the DAG we can associate each fragment to an arc leaving a node
Chunked Multi Triangulations

MT Cuts

- A cut of the DAG defines a new representation
  - Just paste all the fragments above the cut

\[ D^* = D_0 \oplus g_1 \oplus g_4 \]
Chunked Multi Triangulations

MT Cuts

- A cut of the DAG defines a new representation
  - Collect all the fragment floors of cut arcs and you get a new conforming mesh

\[ D^* = D_0 \oplus g_1 \oplus g_4 = f_0 \cup f_2 \cup f_0 \cup f_3 \cup f_1 \cup f_4 \]
Chunked Multi Triangulations

GPU Friendly MT

- Chunked MT assume fragments are triangle patches with proper boundary constraints
  - DAG << original mesh (patches composed by thousands of tri)
  - Structure memory + traversal overhead amortized over thousands of triangles
  - Per-patch optimizations

\[
D^* = D_0 \oplus g_1 \oplus g_4 = f_{0\infty} \cup f_{02} \cup f_{03} \cup f_{13} \cup f_{1\infty} \cup f_{4\infty}
\]
Chunked Multi Triangulations

GPU Friendly MT

- Chunked MT assume regions provide good hierarchical space-partitioning
  - Compact
    - Close-to-spherical
  - Used for computing fast projected error upper bounds
  - Used for visibility queries

\[ D^* = D_0 \oplus g_1 \oplus g_4 = f_{0\infty} \cup f_{02} \cup f_{03} \cup f_{13} \cup f_{1\infty} \cup f_{4\infty} \]
Chunked Multi Triangulations
GPU Friendly MT

**Construction**
- Start with hires triangle soup
- Partition model using a hierarchical space partitioning scheme
- Construct non-leaf cells by bottom-up recombination and simplification of lower level cells
- Assign model space errors to cells

**Rendering**
- Refine conformal hierarchy, render selected precomputed cells
- Project errors to screen
- Dual queue
Chunked Multi Triangulations

DAG problems

• Not all MTs are good MTs!
  – The **topology of dependencies** may lower the adaptivity of the multiresolution structure
    • Cascading dependencies are BAD!!!
  – The **geometry of DAG regions** may cause problems in view-dependent rendering
    • Compact (close-to-spherical) regions for good constant error bounds
    • Long+thin regions are BAD!

• Proposed solutions:
  – SIGGRAPH 2004: Efficient constrained technique (TetraPuzzles)
  – IEEE Viz 2005: General construction technique (V-Partition)
Our contributions

GPU-friendly output-sensitive techniques

- **BDAM - Local Terrain Models**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *EUROGRAPHICS 2003*

- **P-BDAM - Planetary terrain models**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *IEEE Visualization 2003*

- **Adaptive Tetrapuzzles – Dense meshes**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *SIGGRAPH 2004*

- **Layered Point Clouds – Dense clouds**
  Gobbetti/Marton (CRS4)
  *SPBG 2004 / Computers & Graphics 2004*

- **Far Voxels – General**
  Gobbetti/Marton (CRS4)
  *SIGGRAPH 2005*

- **Chunked Multi-Triangulations**
  Gobbetti/Marton (CRS4), Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
  *IEEE Viz 2005*

- **View-dep. Volumetric Model**
  In progress
Adaptive TetraPuzzles
Multiresolution Model for Dense 3D meshes

- **Adaptive TetraPuzzles**: High performance visualization of dense 3D meshes
  - Two-level multiresolution model based on volumetric decomposition
  - Implicit MT based on tetrahedra hierarchy

Cignoni, Ganovelli, Gobbetti, Marton, Ponchio, and Scopigno.
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra

$Target = k$ triangles/chunk
Adaptive TetraPuzzles

Overview

• **Construction**
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra

(6 tetra / diamond) (4 tetra / diamond) (8 tetra / diamond)
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

• **Construction**
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles
Overview

**Construction**
- Start with hires triangle soup
- Partition model using a conformal hierarchy of tetrahedra
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra

\[ k \text{ triangles/chunk} \]
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra

\[ k \text{ triangles/chunk} \]
Adaptive TetraPuzzles

Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
  - Construct non-leaf cells by bottom-up recombination and simplification of lower level cells
Adaptive TetraPuzzles
Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
  – Construct non-leaf cells by bottom-up recombination and simplification of lower level cells
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
  - Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

Diamond external boundary
Diamond internal boundary
Child tetrahedra boundary
Adaptive TetraPuzzles

Overview

• **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
  - Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

Legend:
- **Diamond external boundary**
- **Diamond internal boundary**
- **Child tetrahedra boundary**
Adaptive TetraPuzzles
Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
  – Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

- Diamond external boundary
- Diamond internal boundary
Adaptive TetraPuzzles
Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
  – Construct non-leaf cells by bottom-up recombination and simplification of lower level cells
Adaptive TetraPuzzles
Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
  – Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

NO CRACKS / NO GLOBALLY LOCKED BOUNDARY!
Adaptive TetraPuzzles

Overview

• Construction
  – Start with hires triangle soup
  – Partition model using a conformal hierarchy of tetrahedra
  – Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

• Rendering
  – Refine conformal hierarchy, render selected precomputed cells
Adaptive TetraPuzzles
Overview

- **Construction**
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
  - Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

- **Rendering**
  - Refine conformal hierarchy, render selected precomputed cells

View dependent mesh refinement
Adaptive TetraPuzzles

Overview

• Construction
  - Start with hires triangle soup
  - Partition model using a conformal hierarchy of tetrahedra
  - Construct non-leaf cells by bottom-up recombination and simplification of lower level cells

• Rendering
  - Refine conformal hierarchy, render selected precomputed cells

Independent diamond processing

For each mesh chunk:
  Simplify + stripify +
  compress + eval bounds/error

Out-of-core + parallel

Out-of-core cull+refine traversal / GPU cached optimized meshes
Adaptive TetraPuzzles Results

Michelangelo’s St. Matthew
Source: Digital Michelangelo Project
Data: 374M triangles

Intel Xeon 2.4GHz 1GB
GeForce FX 5800U AGP8X

Adaptive tol Fps: 111.6 Mtri/s 64.7
KTri/f 575.8 Patches/f 378
Adaptive TetraPuzzles

Conclusions

- Yet another multiresolution algorithm for rendering large static meshes
  - First GPU bound method for very large meshes
  - State of the art performance
    - GPU bound
    - >4Mtri/frame at >30 fps on modern GPUs
  - Tuned for large dense models with “well behaved” surface
  - Special case of general MT framework
Our contributions

GPU-friendly output-sensitive techniques

**BDAM - Local Terrain Models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
EUROGRAPHICS 2003

**P-BDAM - Planetary terrain models**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
IEEE Visualization 2003

**Adaptive Tetrapuzzles – Dense meshes**
Gobbetti/Marton (CRS4),
Cignoni/Ganovelli/Ponchio/Scopigno (CNR)
SIGGRAPH 2004

**Layered Point Clouds – Dense clouds**
Gobbetti/Marton (CRS4)
SPBG 2004 / Computers & Graphics 2004

**Far Voxels – General**
Gobbetti/Marton (CRS4)
SIGGRAPH 2005

**Chunked Multi-Triangulations**
Gobbetti/Marton (CRS4), Cignoni/
Ganovelli/Ponchio/Scopigno (CNR)
IEEE Viz 2005

**View-dep. Volumetric Model**
In progress
Our contributions

Far Voxels – General 3D models

- Far Voxels: High performance visualization of arbitrary 3D models
  - Mixed model
  - Seamless integration of occlusion culling with out-of-core data management and multiresolution rendering

Gobbetti and Marton.  
**Far Voxels – A multiresolution Framework for Interactive Rendering of Huge Complex 3D Models on Commodity Graphics Platforms.**  
ACM Transactions on Graphics, 23(4), August 2005  
(Proc. SIGGRAPH 2005).
Far Voxels
Real-time inspection of huge complex models on commodity graphics platforms

- Huge
  - $O(10^9)$ triangles/bytes

- Complex
  - Heterogeneous materials
  - High topological genus
  - Highly variable depth complexity
  - Fine geometric details
  - “Bad” tessellations

Xeon 2.4GHz / 1GB RAM / 70GB SCSI 320 Disk
NVIDIA 6800GT AGP 8X
Far Voxels
Handling Huge Complex 3D models

- Classic multiresolution models
  - Error measured on boundary surfaces
  - LOD construction based on local surface coarsening/simplification operations
  - Visibility culling decoupled from multiresolution

- Hard to apply to models with high detail and complex topology and high depth complexity!
Far Voxels
Handling Huge Complex 3D models

- General purpose technique that targets many model kinds
- Underlying ideas
  - Multi-scale modeling of appearance rather than geometry
  - Volume-based rather than surface-based
  - Tight integration of visibility and LOD construction
  - GPU accelerated (programmability + batching)
Far Voxels
Overview

- Basic building block
  - Far voxel primitive
- Construction
  - BSP of the input model
  - Multiresolution structure
  - Far voxel
- Rendering
  - Selective refinement
  - Occlusion culling
  - Far voxel rendering
- Results
  - Preprocessing
  - Rendering
Far Voxels Overview

- Basic building block
  - Far voxel primitive

- Construction
  - BSP of the input model
  - Multiresolution structure
  - Far voxel

- Rendering
  - Selective refinement
  - Occlusion culling
  - Far voxel rendering

- Results
  - Preprocessing
  - Rendering
Far Voxels

The Far Voxel Concept

• Assumption: opaque surfaces, non participating medium
• Goal is to represent the appearance of complex far geometry
  – Near geometry can be represented at full resolution
Far Voxels
The Far Voxel Concept

- Assumption: opaque surfaces, non-participating medium
- Goal is to represent the appearance of complex far geometry
  - Near geometry can be represented at full resolution
- Idea is to discretize a model into many small volumes located in the neighborhood of surfaces
  - Approximates how a small subvolume of the model reflects the incoming light

=> View-dependent voxel
Far Voxels
The Far Voxel Concept

• A far voxel returns color attenuation given
  – View direction
  – Light direction

\[ \text{Shader}_i(v, l) = BRDF_i(v, l)(n(v).l)_+ \]

• Rendered using a customized vertex shader executed on the GPU

Shader = f (view direction, light direction)
Far Voxels Overview

- Basic building block
  - Far voxel primitive

- Construction
  - BSP of the input model
  - Multiresolution structure
  - Far voxel

- Rendering
  - Selective refinement
  - Occlusion culling
  - Far voxel rendering

- Results
  - Preprocessing
  - Rendering
Far Voxels
Construction overview
Far Voxel Construction overview
Multi-Resolution Techniques for Exploring Extremely Large and Complex Surfaces
Enrico Gobbetti and Fabio Marton, Eurographics 2006 Tutorial

Far Voxels
Construction overview

BSP PARTITION
M PRIMITIVES
VIEW DEPENDENT VOXEL
SAMPLED VOXEL
VOXEL CONTEXT
FITTING
SAMPLING
Far Voxels
Construction overview: Inner nodes

- Sample a model subvolume to build a grid of far voxels
- Voxels are far
  - Project to worst case $\theta_{\text{max}}$
  - Viewed not closer than $d_{\text{min}}$

Section of the 3D grid of far voxels
Far Voxels
Construction overview: Inner nodes

- Sample a model subvolume to build a grid of far voxels
- Voxels are far
  - Project to worst case $\theta_{\text{max}}$
  - Viewed not closer than $d_{\text{min}}$
- Raycasting samples original model and identifies visible voxels
Far Voxels

Construction overview: Inner nodes

- Sample a model subvolume to build a grid of far voxels
- Voxels are far
  - Project to worst case $\theta_{\text{max}}$
  - Viewed not closer than $d_{\text{min}}$
- Raycasting samples original model and identifies visible voxels

Section of the 3D grid of far voxels
Far Voxels

Construction overview: Object Space Occlusion

- Environment occlusion

- Cull interior part of grid of far voxels

Section of the 3D grid of far voxels
Far Voxels
Construction overview: Object Space Occlusion

- Environment occlusion
- Cull interior part of grid of far voxels

Section of the 3D grid of far voxels
Far Voxels
Construction overview: Object Space Occlusion

- Environment occlusion

- Cull interior part of grid of far voxels

- Culls 40% of the high depth complexity Boeing 777 model,
  - worst case $\theta_{\text{max}} = 0.5$ deg
    (~10 pixel tolerance for 1024x1024 viewport using 50deg FOV)

- Minimize artifacts due to leaking of occluded parts of different colors
Far Voxels

Construction overview: Far Voxel

- Consider voxel subvolume

- Samples gathered from unoccluded directions
  - Sample:
    - \((\text{BRDF, } \mathbf{n}) = f(\text{view direction})\)
Far Voxels

Construction overview: Far Voxel

- Consider voxel subvolume

- Samples gathered from unoccluded directions
  - Sample:
    - $(\text{BRDF}, \mathbf{n}) = f(\text{view direction})$

- Compress shading information by fitting samples to a compact analytical representation
Far Voxels

Construction overview: Far Voxel Shaders

- Build all the K different far voxels representations
  - K = flat, smooth...
  - Principal component analysis
- Evaluate each representation error
  - Compare real values (samples) with the voxel approximations from the sample direction

\[ \text{Err}_{(k)} = \sum_i \sum_j \left( \text{BRDF}_{i}^{(sampled)}(v_i, l_j) \max(n_i \cdot l_j, 0) - \text{Shader}^{(k)}(v_i, l_j) \right)^2 \]

- Choose approximation with lowest error
Far Voxel Distribution on a perspective view of the Boeing 777

- Flat shaders
- Smooth shaders (complex local geometry)
- Triangles
Far Voxels

Overview

- Basic building block
  - Far voxel primitive

- Construction
  - BSP of the input model
  - Multiresolution structure
  - Far voxel

- Rendering
  - Selective refinement
  - Occlusion culling
  - Far voxel rendering

- Results
  - Preprocessing
  - Rendering
Far Voxels Rendering

- Hierarchical traversal with coherent culling
  - Stop when out-of view, occluded (GPU feedback), or accurate enough
- Leaf node: Triangle rendering
  - Draw the precomputed triangle strip
- Inner node: Voxel rendering
  - For each far voxel type
    - Enable its shader
    - Draw all its view dependent primitives using glDrawArrays
  - Splat voxels as antialiased point primitives
  - Limits
    - Does not consider primitive opacity
    - Rendering quality similar to one-pass point splat methods (no sorting/blending)
Far Voxels
Overview

- Basic building block
  - Far voxel primitive
- Construction
  - BSP of the input model
  - Multiresolution structure
  - Far voxel
- Rendering
  - Selective refinement
  - Occlusion culling
  - Far voxel rendering

- Results
  - Preprocessing
  - Rendering
**Far Voxels Results**

- Tested on extremely complex heterogeneous surface models
  - St. Matthew, Boeing 777, Richtmyer Meshkov isosurf., all at once
- Tested in a number of situations
  - Single processor / cluster construction
  - Workstation viewing, large scale display

---

373M triangles 14.5 GB
350M triangles 13.7 GB
472M triangles 18.4 GB
1.2G triangles 46.6 GB
Far Voxels Results

- 1-16 Athlon 2200+ CPU, 3 x 70GB ATA 133 Disk (IDE+NFS)
- 1-20K triangles/sec
  - Scales well, limited by slow disk I/O for large meshes
  - Slow!! (but similar to recent adaptive tessellation methods)
- Avg. triangles per leaf 5K
- Avg. voxels per inner node 2.5K
Far Voxels
Results

- Xeon 2.4GHz, 70GB SCSI 320 Disk, GeForce FX6800GT AGP 8x
- Window size: from video resolution to stereo projector display
  - St. Matthew, Boeing, Isosurface: 640 x 480
  - All at once: 640 x 480 and Stereo 2 x 1024 x 768
- Pixel tolerance: [Target 1 | Actual ~0.9 | Max ~10]
- Resident set size limited to ~200 MB
Far Voxels

Conclusions

• General purpose technique that targets many model kinds
  – Seamless integration of
    • multiresolution
    • occlusion culling
    • out-of-core data management
  – High performance
  – Scalability

• Main limitations
  – Slow preprocessing
  – Non-photorealistic rendering quality

Intel Xeon 2.4GHz 1GB, GeForce 6800GT AGP8X
Time for a conclusion, right?
Size matters! Or does it?
A real-time data filtering problem!

- Models of unbounded complexity on limited computers
  - We assume less data on screen \((N)\) than in model \((K \rightarrow \infty)\)
  - Need for output-sensitive techniques \((O(N), \text{ not } O(K))\)

```
<table>
<thead>
<tr>
<th>Storage</th>
<th>Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>O((K=\text{unbounded})) bytes</td>
<td>10-100 Hz</td>
</tr>
<tr>
<td>(triangles, points, ...)</td>
<td>O((N=1M-100M)) pixels</td>
</tr>
<tr>
<td>Limited bandwidth</td>
<td></td>
</tr>
<tr>
<td>(network/disk/RAM/CPU/PCIe/GPU/)</td>
<td></td>
</tr>
</tbody>
</table>
```

View parameters
Application domains / data sources

- Many important application domains
- Models exceed
  - $O(10^8 - 10^9)$ samples
  - $O(10^9)$ bytes
- Varying
  - Dimensionality
  - Topology
  - Sampling distribution

Local Terrain Models
2.5D – Flat – Dense regular sampling

Planetary terrain models
2.5D – Spherical – Dense regular sampling

Laser scanned models
3D – Moderately simple topology – low depth complexity - dense

CAD models
3D – complex topology – high depth complexity – structured - ‘ugly’ mesh

Natural objects / Simulation results
3D – complex topology + high depth complexity + unstructured/high frequency details
Application domains / data sources

- **“Well behaved” surfaces**
- Multiresolution dominates visibility
- Good results with surface based methods based on sequences of local modifications
- GPU-MT / TetraPuzzles / ... already fast/good enough

### Local Terrain Models
2.5D – Flat – Dense regular sampling

### Planetary terrain models
2.5D – Spherical – Dense regular sampling

### Laser scanned models
3D – Moderately simple topology – low depth complexity - dense

### CAD models
3D – complex topology – high depth complexity – structured - ‘ugly’ mesh

### Natural objects / Simulation results
3D – complex topology + high depth complexity + unstructured/high frequency details
Application domains / data sources

**Local Terrain Models**
2.5D – Flat – Dense regular sampling

**Planetary terrain models**
2.5D – Spherical – Dense regular sampling

**Laser scanned models**
3D – Moderately simple topology – low depth complexity - dense

**CAD models**
3D – complex topology – high depth complexity – structured - ‘ugly’ mesh

**Natural objects / Simulation results**
3D – complex topology + high depth complexity + unstructured/high frequency details

- Highly complex surfaces
- Visibility needs to be tightly combined with LODs
- Need to go to volumetric models
- Far Voxel is a state-of-the-art solution
- Still not the final world...
So many things, so little time...

- More info:
  http://www.crs4.it/vic/
  http://vcg.isti.cnr.it/

- Q&A: Your turn...