Octree CT Volume Based Reconstruction and Shape Extraction for Processing Massive X-ray Projection Data

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Abstract

Demands on high-resolution CT scanning is rapidly increasing, which are intended for precise shape measurement and internal tiny-structure analysis in industrial applications. In order to satisfy such demands, cone-beam type CT scanners equipped with high-resolution (e.g. 4K by 4K pixels) flat-panel detectors are recently available. Since the projection data obtained from high-resolution CT scanners is massive (e.g. several hundred Giga bytes), processing the data is computationally intensive. Aimed to reduce the computational costs, several researchers have proposed to use adaptively sampled grid data structures, i.e. octree CT volumes, rather than the conventional uniformly sampled grid. However, these researches are mainly focused on only CT reconstruction.

In this research, we propose an efficient method combining reconstruction and shape extraction on octree CT volumes. The proposed method generates a precise mesh representing a single material object scanned by a high-resolution CT scanner. In the CT reconstruction stage, a pyramidal projection data set is created and used for FDK reconstruction of a coarse-to-fine octree volume. We utilize a simple octree-subdivision rule with analyzing a local variation of CT values according to changes of the subdivision levels. In the shape extraction stage, the dual marching cube algorithm, in which the standard marching cubes are applied to the grid cells constructed from the dual graph of an octree, is conducted to generate an initial mesh as an isosurface. We take into account the volume fractions of the material in the cells for interpolating the CT values inside the cells. The accuracy of the initial mesh is further improved by moving mesh vertices to the maxima of CT gradients. For estimating the gradients, we used the analytical differentials of FDK formula in order to avoid the difficulty of applying finite difference methods to octree structures.
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2. Isosurface extraction on octree CT volume
3. Gradient-maxima surface extraction
Algorithm Overview: Reconstruction of Octree CT Volume

1. Construct pyramidal projection data with recursive down-sampling
   • Shepp-Logan filter is firstly applied to the finest images

2. Reconstruct a CT volume on an octree coarse-to-fine

Construction of Pyramidal Projection Data

• Recursive down-sampling procedure
  • 2 by 2 binning for each projection image
  • Skip even-numbered projection images
Division Rule of Octree Cells (Octants)

- If the change of CT values are small via octant division, then the division-level is kept.
  - CT values are evaluated at the octant center by the integration of backprojection values
  - Change of CT value: \( \varepsilon \equiv \max \left( \max(v^{l+1}_i - v^l), \max(v^l - v^{l+1}_i) \right) \)

Result of CT Reconstruction: Aluminum Piston Head

- Projection Data: 2000 images with 2048 \( \times \) 2048 pixels
- Level 0: \( 128^3 \), 4 times adaptive divisions.

Filtering: 220 sec.
Backprojection: 41 sec.
(including file IO)
Octree data size: 208 MB

by using
1 \( \times \) GeForce GTX 1080
1 \( \times \) Xeon E5-1650 3.6 GHz
Result of CT Reconstruction:
Aluminum Step Cylinder

- Projection Data: 4000 images with $4096 \times 4096$ pixels
- Level 0: $128^3$, 5 times adaptive divisions.

Filtering: 3295 sec.
Backprojection: 772 sec. (including file IO)
Octree data size: 806 MB

by using
1 $\times$ GeForce GTX 1080
1 $\times$ Xeon E5-1650 3.6 GHz

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Algorithm Overview:
Isosurface Extraction on Octree CT Volume
Dual Marching Cubes for CT data [1]

1. Create dual-grid of octree
   • Conversion octants into grid-points, and grid-points into cells.

2. Apply marching cube algorithm to dual-cells
   • Points on isosurface are computed with taking into account octant-sizes.


Result of Isosurface Extraction:
Aluminum Piston Head

Dual-grid generation: 7 sec.
Marching cubes: 29 sec.
(including file IO)
Mesh triangles: 24 millions
STL size = 6 \times \text{octree size by using}
12 cores: Xeon E5-1650 3.6 GHz
Result of Isosurface Extraction:
Aluminum Step Cylinder

- Reasonable time for mesh generation, but accuracy is not high because of CT artifacts.

Dual-grid generation: 32 sec.
Marching cubes: 55 sec.
(including file IO)
Mesh triangles: 60 millions

Colored by deviation from CMM cylinders

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Gradient-maxima Surface for Improving Measurement Accuracy

• The surface point is defined as a local maximum of the gradient-norm $\|\nabla f\|$ along the gradient-direction.

$$g \equiv (\nabla f)^t \nabla \|\nabla f\| = \frac{(\nabla f)^t (\nabla^2 f)(\nabla f)}{\|\nabla f\|^2} = 0$$

Estimation of Gradient $\nabla f$ and Hessian $\nabla^2 f$ on Octree CT Volume

• Integration of derivatives of projection data
  • Analytical derivatives of FDK-formula
  • Grid-free estimation on CT volume

$$\frac{\partial^{\alpha+\beta+\gamma}}{\partial x^\alpha \partial y^\beta \partial z^\gamma} f \equiv \frac{1}{2} \int_0^{2\pi} p^{-(\alpha+\beta+\gamma+2)} (\cos \theta)^\alpha (-\sin \theta)^\beta \frac{\partial^{\alpha+\beta+\gamma}}{\partial u^\alpha \partial v^\beta} S \, d\theta$$

$[(x, y, z)$: coord. of CT volume, $(u, v)$: coord. of projection image, $P$: magnification$]$
Extraction of Gradient-maxima Surface

1. Label inside / outside by thresholding CT values
   • The initial surface is the isosurface

2. Resolve inconsistency to $g = 0$
   by iterative local re-labeling
   • Move the surface $g = 0$ along dual-grid edges

Result of Gradient-maxima Surface Extraction:
Aluminum Step Cylinder

• The accuracy was improved,
  but it is noise sensitive because of high-order derivatives

- Derivative estimation: 2304 sec.
- Dual-grid generation: 32 sec.
- Marching cubes: 72 sec.
  (including file IO)
- Mesh triangles: 67 millions

by using
  1 × GeForce GTX 1080
  12 cores: Xeon E5-1650 3.6 GHz