Converting Multi-Axis Machine Tools into Subtractive 3D Printers by using Intelligent Discrete Geometry Data Structures designed for Parallel and Distributed Computing

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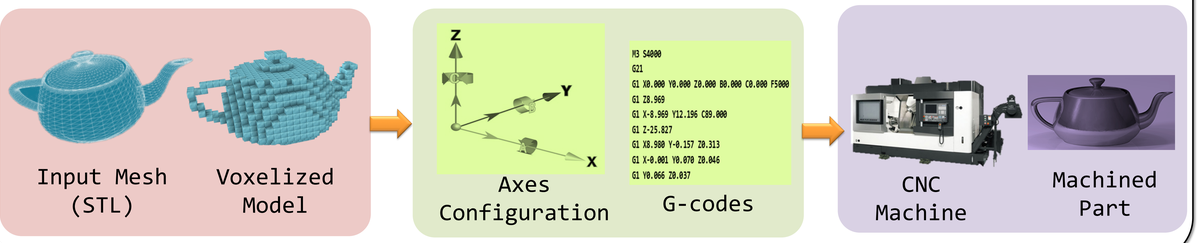
Research Objective

CNC tool-path planning with the ease of programmability of 3D Printing and precision of Subtractive Manufacturing

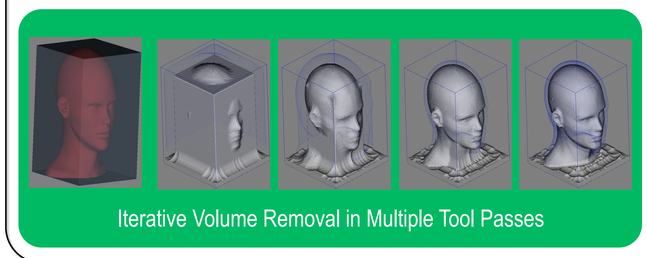
- **Toolpath Automation**
  - Use of alternative CAD representation.
  - Voxel instead of BREP or CSG to simplify 3D contour offset computation.

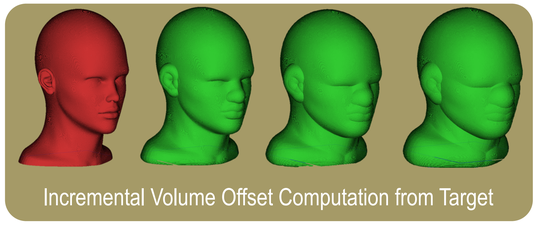
- **High-Resolution Geometry Processing**
  - Novel compact representation of sparse 3D Data.
  - Leverage GPGPU acceleration.



Iterative Toolpath Generation from Successive Volume Offsetting

Offset volume provides surface where a tool of a given radius travels without over/under-cutting.



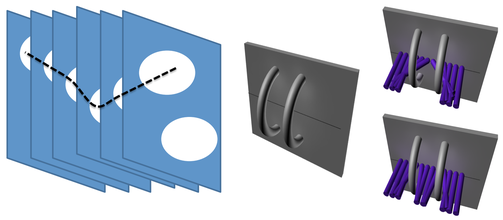


Successive offset volumes provide a sequence of XYZ points for a tool path.

Tool Orientation and Tool Retractions

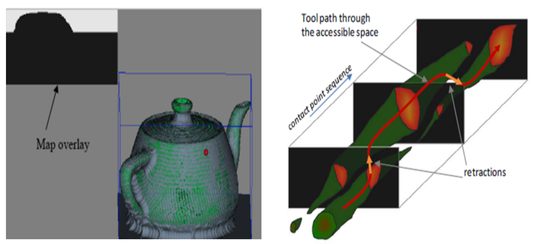
A tool positioned on the offset volume must assume an orientation that avoids collisions.

An "accessibility map" provides allowable orientations for the tool.



These events in accessibility space correspond to tool retractions.

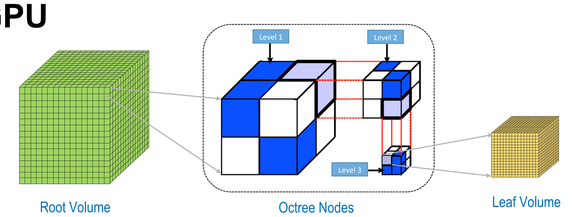
Sometimes the path encounters a "dead end" in accessibility space and must jump to a new open "tunnel" in order to continue.

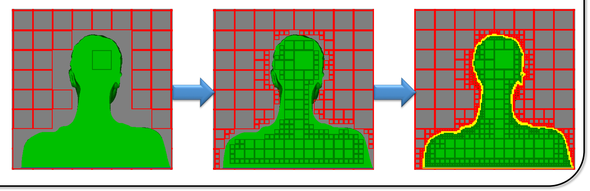


Stacked in sequence, the accessibility maps form an accessibility space.

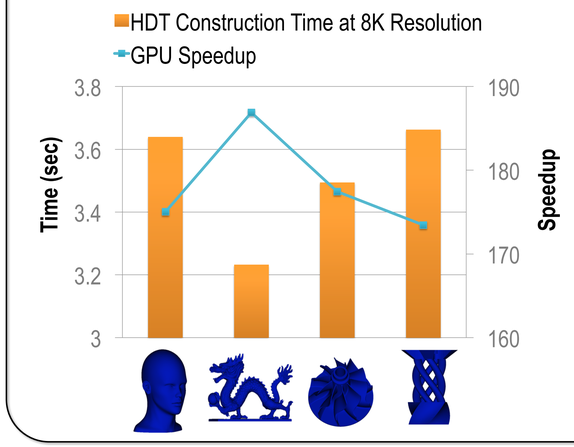
Extreme-Resolution Voxel Processing on GPU

- Grid-based volume modeling → $O(n^3)$ memory
- Octree memory consumption is optimal → height log_2 (*Resolution*)
- **Hybrid Dynamic Tree (HDT)** integrates Octree and Grid layout
  - Entire volume space is divided over a 3D grid of root nodes.
  - Each intersecting root is adaptively sub-partitioned.
  - Spatial decomposition terminates when leaf element reaches target resolution (yellow nodes).
  - Each leaf element comprises a group of 16 x 16 x 16 voxels.
  - A 4-level HDT represents up to 16 x 2^4 x 16 = 4K resolution.

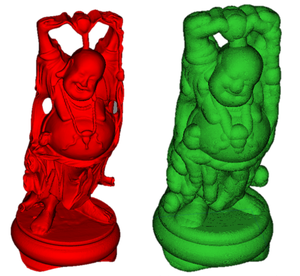




Evaluations of HDT Construction and Offset Surface Computation



Offset surface computation achieves 10X speedup compared to best-performing 8-core CPU implementation* (38X of single-core performance) on a NVIDIA GTX 780Ti card.



Buddha model (1M triangles) dilated by 2% of of the diagonal length of the bounding box

* Fast Intersection-free Offset Surface Generation from Freeform Models with Triangular Meshes, IEEE Transactions on Automation Science and Engineering, 2011.

Machining Simulation and Resulting Parts: Design to Production Flow