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Real-time Interaction with 3D Medical Imaging using 3D textures

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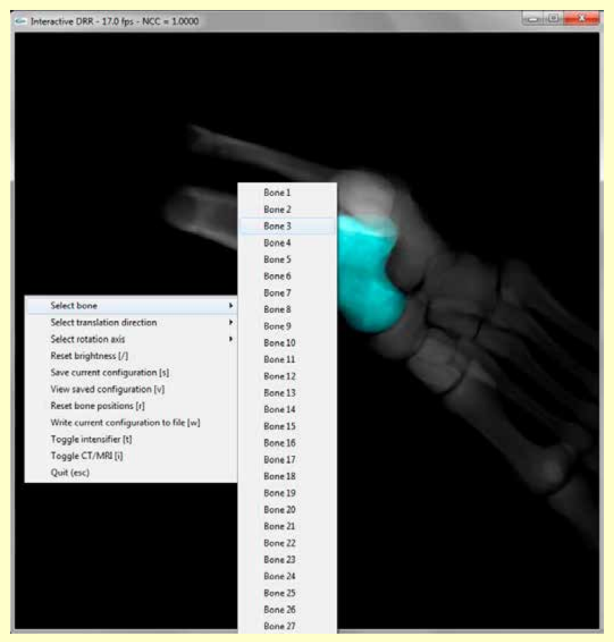
We present two applications employing CUDA's 3D texture memory to achieve real-time interaction with volumetric imaging data.
Input data is an image stack segmented to specify the voxel set for each structure.

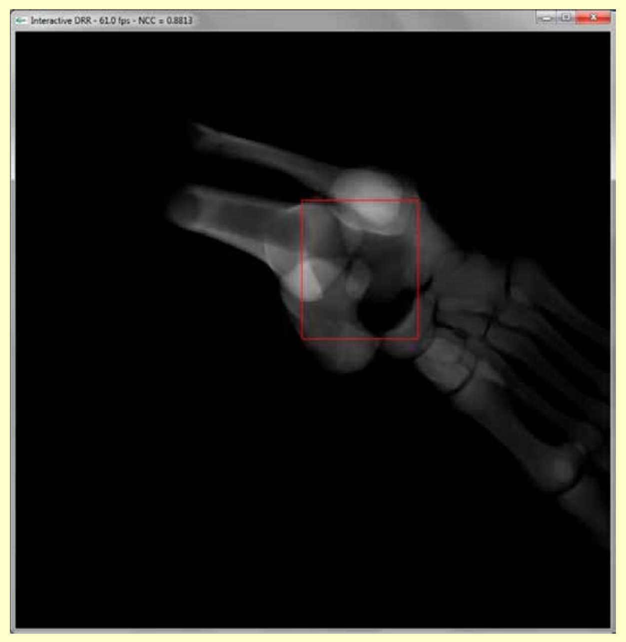
DRRACC:
CUDA accelerated simulation of Digitally Reconstructed Radiographs (DRRs)

- Applications involve 2D/3D registration for biomechanical analysis and imaging-guided therapies: Simulate x-ray image by projection of 3D CT scan data and compare with 2D fluoroscope image.
- Employ the basic imaging model of a focal point (here an x-ray source) connected by a ray to each of the pixels in an imaging plane.
- Input data: 3D array of floating point densities (from CT) and 3D array of integer labels identifying the voxels that belong to each bone (from segmentation).
- Similarities to volume rendering:
  - Basic computation along a ray: Sum densities as the ray passes through the voxel set.
  - Basic approach to parallelization: Launch one thread per pixel.
  - 3D texture +spatial coherence = efficient access to data set too large for shared memory.
- Key difference: Support independent motion of multiple segmented objects (bones).
- Approach to achieving independent manipulation of bones:
  - Apply inverse kinematic transformation for each bone and compute its image (summing only contributions from voxels with the specified integer label)
  - Composite the individual bone images by summing intensities for each pixel.
- Bookkeeping for contributions from each bone:
  - Use 3D texture with interpolated floating point data for CT density data.
  - Use 3D texture with integer data and nearest neighbor sampling for bone ID labels.
  - Device vectors from Thrust Libraries store image data for adding intensities and computing correlations between simulated and reference images.

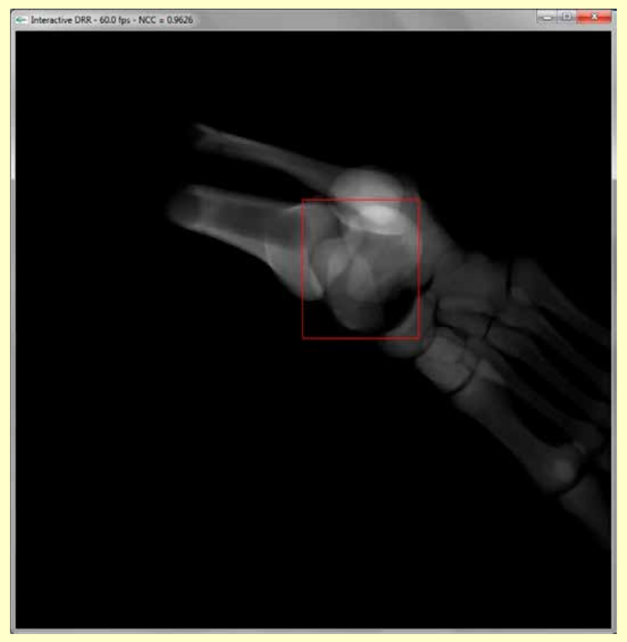
Reference configuration



Select bone/transformation



DRR with translated talus



DRR with rotated talus

GridModeler:
Proof of concept for CAD based on Signed Distance Image Stacks

- Obtain signed distance "image stack" as by-product of level set-based segmentation, by applying Danielsson's algorithm to voxel set, or by "virtual scan" of CAD object.
  ⇒ **Scanned anatomy and engineering objects can happily co-exist and interact!**
- No polygons are involved in producing the screen shots shown below. Each solid is defined by a function (f-rep modeling), and the sign of the function classifies a point as interior or exterior.
- Choose a particularly useful defining function: Signed Distance Function (SDF)
- Our f-rep models consist of an image stack or grid of SDF values along with an interpolant to support evaluation at points off the grid (i.e. points not located at voxel centers).
- Fast linear interpolation by texture processor sufficient for many operations, but conceptually employ wavelet interpolant to guarantee existence (and efficient evaluation) of derivatives and ensure desired surface smoothness.
- Visualize by casting a ray from the viewpoint through the voxel set toward each pixel in a planar array.
- The parallelization approach again involves launching a kernel with one thread for each ray/pixel. Solids are treated as opaque with a simple shading model where intensity is determined by the angle between the ray and the vector normal to the surface of the solid where it is intersected by the ray. The surface of the solid corresponds to the zero level set of the function, so the relevant kernel operation now involves root-finding (i.e. finding the intersection of the ray with the surface of an object corresponds to finding a zero of the object's defining function evaluated on the ray) and evaluation of the gradient of the function at the intersection point.
  - Signed distance functions support fast, reliable root-finding. Taking steps along the ray equal to the current magnitude of the function ensure that no intersections are missed.
  - Wavelets enable computation of derivatives via correlation with connection coefficient vector.
- Create a 3D texture to store signed distance grid for each object.
- Boolean operations performed by parallel evaluation of comparisons at corresponding grid points (by launching a kernel on a 3D grid with one thread be voxel).

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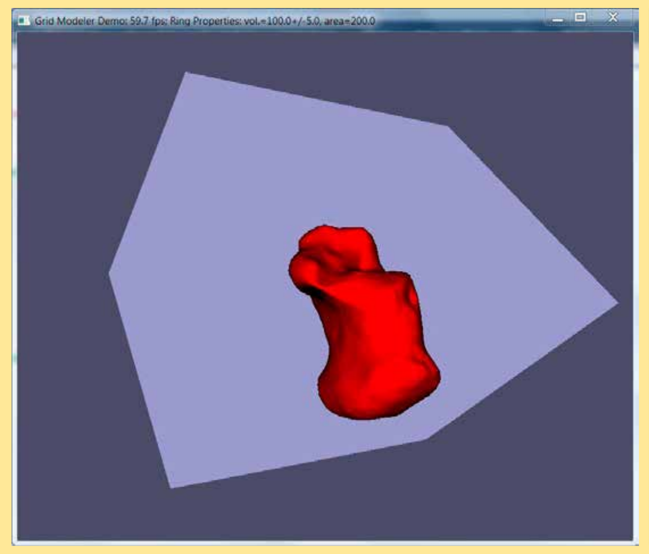
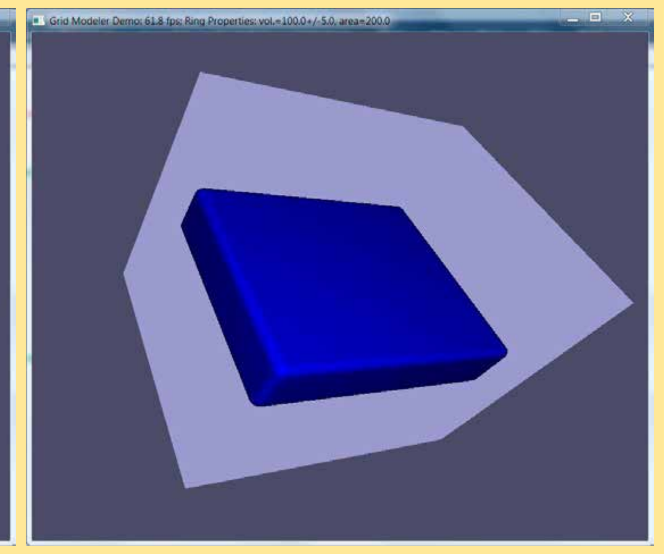
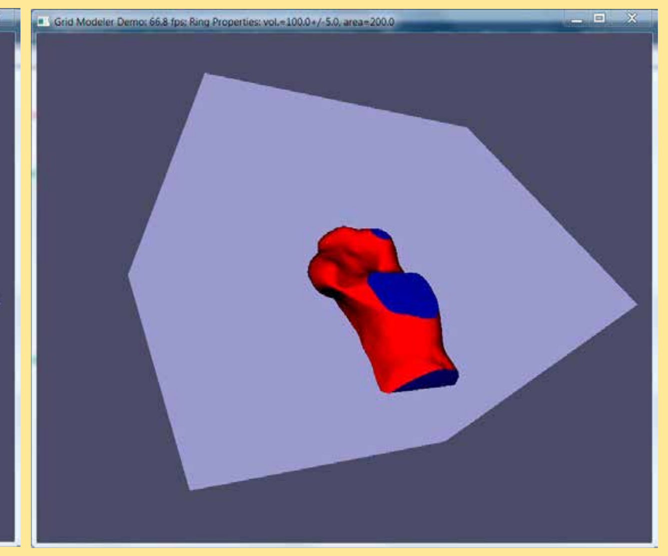


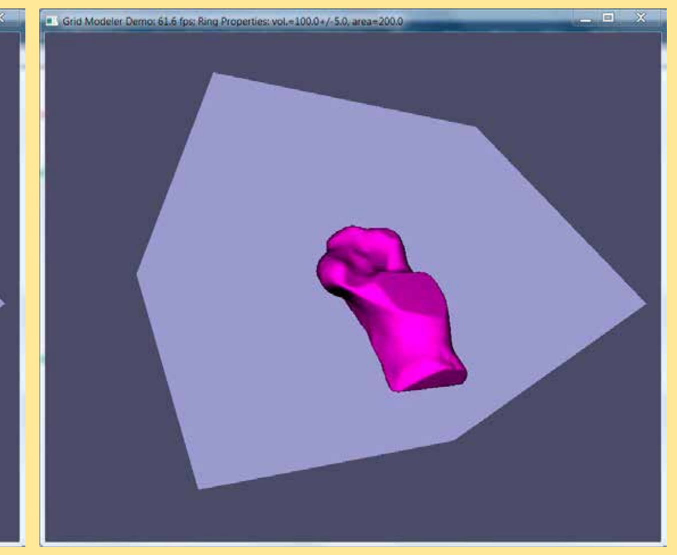
Calcaneus from segmented CT data



Offset slab from virtual scan of implicit function



Intersection of slab and calcaneus



New object (i.e. new 3D SDF grid) created by pointwise comparison on the grid

Publications

[1] Marchelli, G., Haynor, D., Ledoux, W., Ganter, M., and Storti, D., Graphical User Interface for Human Intervention in 2D-3D Registration of Medical Images, Proceedings of the 9th International Conference on Multibody Systems, Nonlinear Dynamics and Control, Paper #DETC2013-13659.
[2] Marchelli, G., Haynor, D., Ledoux, W., Tsai, R., and Storti, D., A flexible toolkit for rapid GPU-based generation of DRRs for 2D-3D registration, SPIE paper #8669-47, 2013.
[3] Storti, D., Ganter, M., Ledoux, W., Ching, R., Hu, Y. P., Haynor, D., Artifact vs. Anatomy: Dealing with Conflict of Geometric Modeling Descriptions, *SAE 2007 Transactions Journal of Passenger Cars: Electronic and Electrical Systems*, Paper #2007-01-2450, Seattle, WA, 2007.
[4] Hu,Y., Haynor,D. , Fassbind,M., Rohr,E., and Ledoux,W., "Image Segmentation and Registration for the Analysis of Joint Motion from 3D MRI," Proc. SPIE **6141**, pp. 133-142, *Medical Imaging: Visualization, Image-Guided Procedures,&Display*, 2006.

Further information and Acknowledgment

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