Efficient projection and deformation of volumetric shape and intensity models for accurate simulation of X-ray images

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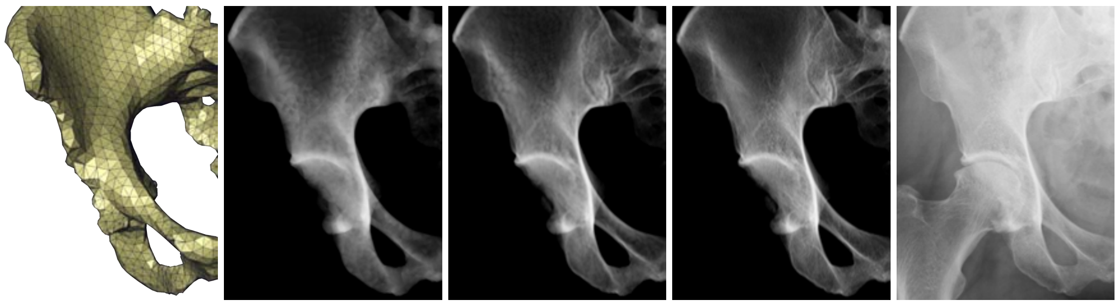

(a) (b) (c) (d) (e)

Figure 1: *(a) Tetrahedral grid consisting of 56k tetrahedra modelling a pelvis, virtual X-rays of the same grid with (b) Bernstein polynomial intensity distribution of degree* $d = 0$ *and (c)* $d = 3$*, (d) ground truth ray-casting from CT, (e) clinical X-ray of the pelvis.*

1 Introduction

A common concept for reconstructing a patient's 3D anatomy based on a single or a few X-ray images is to project many variations of a deformable 3D shape onto an image plane with a known X-ray setup. These projections are then compared to a patient's X-ray within an optimization framework. It is assumed that the projected model instance which depicts the 2D shape in the X-ray image(s) best also approximates the underlying 3D anatomy. Our goal is to rapidly generate large quantities of radiograph images that mimic the appearance of clinical X-ray, allowing for a direct image-based comparison between virtual and clinical X-rays during the reconstruction process.

In previous work, Sadowsky et al. [Sadowsky and Cohen 2006] simulate X-ray images based on statistical shape and intensity models (SSIMs) as proposed by Yao [Yao 2002] using a projected tetrahedra approach. For the purpose of anatomy reconstruction from 2D X-rays, they perform the model deformation on the CPU. Consequently, the geometry and intensity information has to be copied to the GPU memory after the model is altered, limiting the performance of their approach.

We present an extension to the work of Yao and Sadowksy et al. that efficiently generates virtual X-ray images from deformable shape and intensity models. The intensity distribution representing the bone density is described as Bernstein polynomial functions on tetrahedral cells, allowing for accurate density representation even on coarse grids. Unlike previous methods, our approach is implemented entirely on the GPU, thus avoiding time consuming copy operations between GPU- and system-memory.

2 Our Approach

A SSIM, as employed in this work, models the mean shape (a tetrahedral grid) and intensity distribution (coefficients to Bernstein polynomials) plus their specific variations by means of a principal component analysis (PCA). The mean and eigenvector components of the SSIM are stored entirely in graphics texture memory.

To deform and project the model, one point primitive is rendered per tetrahedron and the shape and intensity distribution is deformed by computing a linear combination of deformation parameters and eigenvector components in the vertex shader stage. We then stream the deformed tetrahedra and corresponding Bernstein polynomial coefficients through the geometry and fragment stages of the graphics pipeline. The entrance parameters of the rays of sight on the front-facets of the tetrahedra are interpolated linearly between tetrahedral vertices. Our approach determines the ray exit parameters and their traversal depths in the fragment shader stage using direct ray-facet intersection tests in barycentric coordinates, avoiding any explicit branching or looping of shader programs. Both the entrance and exit parameters are then applied to integrate the Bernstein density functions in the fragment shader stage. By blending the results onto each other, the contribution of every tetrahedron in the grid is accumulated according to the Beer-Lambert law of attenuation.

Our evaluation shows that for a Bernstein polynomial degree up to two, the combined deformation and projection on the GPU leads to a performance increase by a factor of at least three to seven compared to the CPU-based deformation. Even while applying more than 30 deformation parameters on an SSIM featuring 615k tetrahedra, the GPU implementation still reaches interactive rates. Preliminary results also indicate that the quality of the virtual X-ray images is suitable for optimization-driven reconstruction processes that utilize image-based comparison measurements such as normalized mutual information.

References

SADOWSKY, O., AND COHEN, J. 2006. Projected tetrahedra revisited: A barycentric formulation applied to digital radiograph reconstruction using higher-order attenuation functions. *IEEE Trans Vis Comput Graph 12*, 4, 461–73.

YAO, J. 2002. *A statistical bone density atlas and deformable medical image registration*. PhD thesis, Johns Hopkins University.

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